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Review on battery thermal control systems for energy efficient electric vehicles

[1]S.V.P.S. Lahari ,S.Harsha vardhan,P.Chinni Krishna,V.Rohith,P.Murali Mohan Rao,P.S.P.Lal

[2]A. Lakshmu Naidu

[1]Student, GMR IT, Mechanical Department, Rajam, India.
[2]Assistant Professor, GMR IT, Mechanical Department, Rajam, India.

Abstract :

This paper provides an overview of the battery thermal management and control systems (BTMSs) based on the various researches This across the globe. Lithium-ion batteries are widely used for electric vehicles (EVs) and hybrid electric vehicles (HEVs) due to high energy density, high specific energy, light weight, high voltage output, low maintenance cost, long service life. However, among all these it is important to maintain proper temperature range as lithium ion is sensitive to temperature. The operating temperature of a lithium-ion battery ranges from range 15◦C to 35◦C and this is being achieved by a battery thermal management system (BTMSs). This paper reviewed about the actual mechanism of heat generation and various temperature control systems such as phase change materials (PCM), air convection and liquid convection, heat pipe, refrigeration cooling methods. Finally, a summary is made using different design structure based on maximum temperature and temperature uniformity in each cooling techniques at different testing conditions.

Keywords: Battery thermal management system Electric vehicles E- vehicles Battery cooling Lithium-ion

1.Introduction

Interest on electric vehicles (EVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) has significantly increased, as environmental regulations on greenhouse gas (GHG) emission have been strengthened. The fundamental challenge for EVs is to find an appropriate energy storage system that can support high mileage, fast charging and high-performance driving [1]. Recently, rechargeable lithium-ion (Li-ion) batteries are regarded as the most suitable energy storage device for EVs because of their higher energy density, higher specific power, lighter weight, lower self-discharge rates, higher recyclability and longer cycle life than other rechargeable batteries such as leadacid, nickel–cadmium (Ni-Cd), nickel-metal hydride (Ni-MH) batteries [2]. Extensive research on battery thermal management (BTM) has been undertaken to investigate, develop, and introduce technologies and methodologies for thermally controlling the battery cells temperature range and thereby improving their efficiency and functionality [3]. Phase change materials (PCMs), air cooling, and liquid cooling are mostly used in battery thermal management systems (BTMSs) [4]. Liquid and air-cooling systems have been the most often employed technologies due to their ease of usage and low cost. However, it has been discovered that various technologies using heat pipes (HPs) have been employed to both cool and heat batteries, as well as improve thermal management [5].

This review paper mainly focussing on work done by researchers during the past few years in understanding the concept of BTMS and the mechanism of heat generation. It includes effort taken by the various investigator in developing the temperature controlling system using air cooling, liquid cooling and phase change material with their benefits and challenges. Further, a detailed study is performed on phase change material its usefulness, difficulties and possible ways to overcome all these difficulties using different techniques like fin insertion, composite PCM and encapsulation of PCM. A summary of different designs of thermal management systems developed by peoples all over the world in each technique is compared based on maximum temperature and temperature uniformity to get the key information regarding recent technological developments in battery thermal management system. This will help readers not only in concentrating in those parts which receive the high influence of heat generation but also improving the performance of battery thermal management system using various techniques discussed in this paper.

2. Concept of BTMS

A battery thermal management system is essentially the brain of a battery pack. A battery pack consists of several battery cells arranged in different configurations of series, parallel, and combination of the same. Lithiumion batteries are the most preferable one for commercial purpose as it dominates the performance of other types of batteries. The performance of the battery depends upon an electrochemical process which is ultimately temperature dependent. Arrhenius law states that the rate of chemical reaction increases exponentially with the temperature rise. This uneven temperature distribution causes temperature non-uniformity which leads to a reduction in the life cycle and cell performance. Battery temperature varies due to internal heat generation during the charging and discharging process. Ohmic heat, the heat of mixing, enthalpy heating, and entropy change of the electrochemical reaction contribute to the internal heat generation within a battery. During charging, the electrochemical reaction is endothermic while discharging it is exothermic. Internal generation during chargedischarge cycles is one of the disputes to employing lithium-ion batteries in EVs and HEVs [6]. Therefore, to overcome these disputes, BTMS plays a crucial role in battery pack life and its overall performance.

3. Classification of BTMS

BTMS is mainly classified based on power consumption, heat transfer medium, and contact between the coolant and battery surface [7]. Further, it can be classified based on the configuration of cells arranged in a battery pack. Air cooling, liquid cooling, and phase change materials (PCM) cooling are the conventional techniques of battery cooling [8, 9, 10].

4. Concept of heat generation mechanism

The thermal characteristics of lithiumion battery are determined by the complex electrochemical reaction and electric-thermal conversion. The heat generation consists of four components: reaction heat, ohmic heat, polarization heat and secondary reaction heat. The secondary reaction heat, such as the decomposition heat of small part of electrode or electrolyte at high temperatures, is generally ignored. Reaction heat refers to the heat generated by the insertion and deintercalation of lithium ions between positive and negative electrodes, which is related to the entropy change. Polarization is the phenomenon that the actual potential deviates from the equilibrium potential as the current flows through the electrode surface. The polarization heat is affected by the voltage difference between average terminal voltage and open circuit voltage. It is related to battery type, current, ambient temperature, etc. Ohmic heat is irreversible heat associated with current and internal resistance.

Bernardi et al. [11] constructed a simplified heat generation model on account of the internal resistance and entropy increasing reaction principle. The first term $I(U_{oc} - U_o)$ refers to ohmic heat and polarized heat and could be substituted with IR_t, where R_t represents the total resistance, including ohmic resistance and polarization resistance. Ohmic resistance is related to material properties and battery geometry. The polarization resistance is related to SOC and depends on the polarization of anode and cathode, whose value is positively correlated with current density. The latter term is the reversible heat during the entropy change. $T(dU_{oc}/dT)$ is the temperature influence coefficient, and relates to the electrochemical reactions.

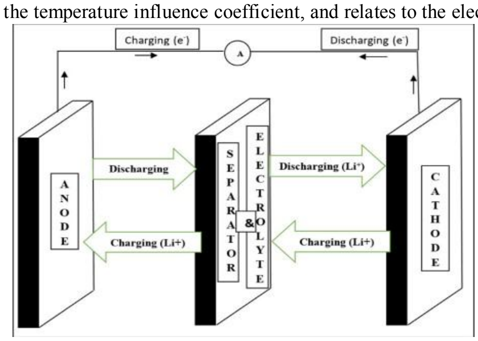


Figure 1 Schematic of Lithium-ion cell

Lithium-ion battery consist of two parts: anode and cathode. Both positive electrode cathode and negative electrode anode are intercalated material with sufficient electronic conductivity. The current collector with high potential of aluminium material is used at the cathode and low potential copper current collector is used at anode since high

Table 1

Properties of alkyl solvents heat is developed at the positive electrode. A separator is attached between two electrodes to prevent electrical contact. An electrolyte (alkyl carbonate+$LiPF_6$) allows ions to transfer through it. At present alkyl carbonates like EC

(Ethylene carbonate), PC (Propylene carbonate), DMC (Dimethyl carbonate), DEC (Diethyl carbonate), EMC (Ethyl methyl carbonate) are utilized in the lithium-ion battery. Their basic properties are shown in Table 1.

During charging, oxidation and reduction reaction will take place at cathode and anode respectively and lithium ions will shift from the cathode towards anode through the electrolyte by receiving energy from an external source. While in the discharging process, lithium ions bring back to the cathode through electrolyte producing the energy. In both cases, electrons will move in the opposite direction in respect of lithium ions, in the outer circuit [12]. The chemical reaction occurring during charging and discharging which leads to heat generation of a battery cell. Heat generation or heat loss distribution in a battery cell is due to reversible heat (Qrev) and irreversible heat (Qirr) [13]. Many researchers are making efforts to understand the mechanism behind the heat generation and its relation with different components in battery cells.

4.1. Reversible heat

Reversible heat is generated at cathode and anode. It is entropic heat originates from reversible entropy change during the electro chemical reaction. It increases as charging rates increases from 1C to 2C and then it decreases at 3C during charging and discharging. This heat may be endothermic or exothermic type. There is exothermic heat release at anode till 0.5 DOD (depth of discharge) and endothermic beyond that. For cathode endothermic heat release till 0.2 DOD and exothermic beyond that. This heat release is due to the insertion and de-insertion of lithium ions in electrodes. Entropic heat loss may be positive or negative depending on the charging or discharging of a battery cell. Thus, for a complete cycle, it has a very small value and can be neglected in certain cases. Hence in most of the HEV and EV applications, reversible heat losses are neglected.

4.2. Irreversible heat

Irreversible heat is generated at electrodes, electrolyte, and current collector. It has a major contribution to more than 70% of total heat. It is characterized by the Joule heating of the battery cell. It directly depends on C-rate. It is an exothermic kind of heat.

Alkyl solvents	**Dielectric constant**	**Viscosity (at 25°C) mPa.s**	**Flashpoint (°C)**	**Boiling (°C) point**	**Melting point (°C)**
EC	**90**	**1.9 (at 40°C)**	**143**	**238**	**36**
PC	**65**	**2.5**	**138**	**242**	**-49**
DMC	**3.1**	**0.59**	**17**	**90**	**5**
DEC	**2.8**	**0.75**	**25**	**127**	**-74**
EMC	**3**	**0.65**	**23**	**108**	**-53**

5. Cooling methods for LIBs

EV LIBs at high temperature must be cooled to augment the performance. Different methods have been proposed, including the air cooling, the liquid cooling and the PCM cooling technologies.

5.1. Air-cooled BTMS

Air-cooled BTMS uses air as a medium [14]. It has a simple design, low operating and maintenance cost, and has been applied to many EVs. There are three types of air-cooled BTMS depending on the source of air:
The first type uses the outside air only as a cooling medium.
The second type uses a combination of the outside air and the preconditioned cabin air through base vapor compression cycle (VCC).
The third type is based on the use of cooled air from an evaporator that is additionally configured to the basic VCC in certain scenarios where the cooling requirements of the cabin and battery may be different.
Both the natural convection or passive convection and forced convection or active convection can be utilized as air cooling strategies in BTMS.

5.1.1. Natural convection BTMS

Air cooling has been applied in commercial applications and is studied widely as a traditional system. The heat transfer coefficient of natural air cooling is not comparable to forced-air cooling due to the low energy densities [15]. Natural convection is hardly studied or used even though it has simplicity, less cost, and lightweight.

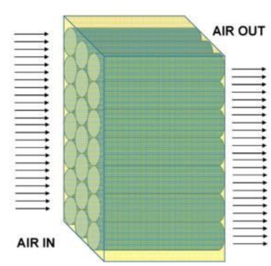


Figure 2 natural cooling

5.1.2. Forced convection BTMS

Forced convection BTMS is commonly used in the car industry. To maintain the optimum temperature of the battery pack, commercial EVs like Toyota Prius and Honda Insight directly blow the conditioned cabinet air into the battery module [16]. Park [17] designed the simulation model for thermal resistance with forced inlet airflow and outlet ducts and concluded that it used tapered manifold relative to other forms of airflow shapes. The installation of pressure relief ventilation in the outlet air duct will further reduce the maximum temperature and increase the uniformity of the temperature. It can also be useful if the battery releases toxic gases [18]. Air inlet velocity, pin and fin arrangements, thermal energy discharge rates, temperature distribution, porous insert length as well as metal foam permeability and porosity are all recorded investigations. Yu et al. [19] developed a two-directional BTMS airflow system that separates air channels and fans. It is found that the cubic configuration is the most optimal in terms of thermal stability and cost-effectiveness. Further, hexagonal array type of cells was found to be the most suitable structure in terms of spatial quality. In addition, the fan that is mounted on top of the battery pack has achieved the best efficiency in cooling. The highest performance was achieved by the distributed thin air ducts proposed by Fathabadi [20].

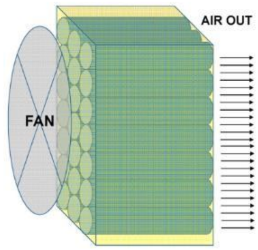


Figure 3 forced convection.

5.2. Secondary liquid-cooled BTMS

To overcome the disadvantages of air cooling, secondary liquid cooling has been introduced, because the cabin air was insufficient in case of high-power application to keep the battery in the normal working temperature shows the secondary loop liquid cooling system (SLLCS), in which the liquidbased BTMS has two loops. The first loop with the blue line is the refrigerant loop and the second with the red colour is connected via chiller. A three-way expansion valve is used and its operation depends on the environmental factors and the cooling load. When the ambient temperature is less than the temperature of the liquid coolant, the liquid coolant can flow to the radiator so that the liquid is cooled by the outside air. Now, when the exterior temperature of the battery is higher than the liquid coolant temperature, liquid flow through the chiller is needed to exchange heat with the refrigerant so that the battery can be easily cooled by interchanging the direction of flow of the refrigerant with the aid of the multiway valve. However, since the battery temperature needs to be controlled properly at different battery charges and ambient temperatures, the actual EVs use the BTMS secondary loop liquid cooling system [21].To manage the battery temperature with respect to the outer ambient temperature, most of the authentic BTMS in EVs use SLLCS. Because SLLCS has various performance advantages as listed below:

Under extreme environmental conditions with rapid charge and discharge conditions, SLLCS can continue to maintain normal battery pack temperature

The liquid cooling system has a higher heat transfer capability

Higher heat mass flow rate

Capability to withstand the high temperature

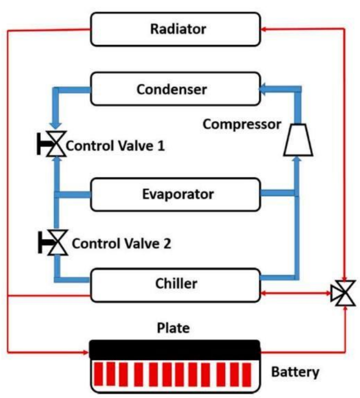


Figure 4 Secondary loop liquid cooling system.

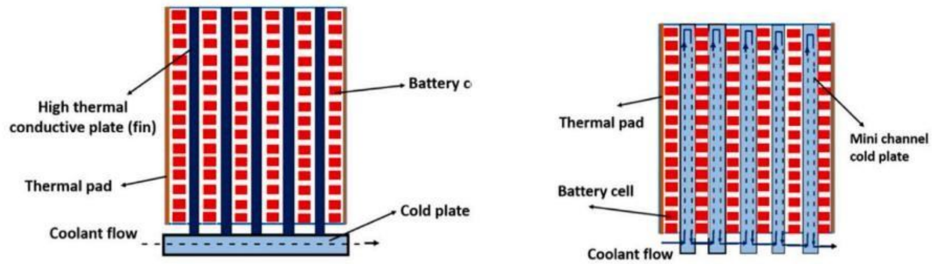
SLLCSs are mainly classified into two types on the basis of positioning and type of heat sink plate. The schematic of the two types is shown in Fig. 5 [22].

Type 1 - Fin cooling method:

In the fin cooling method, fins are inserted between the battery cells, and the cold plate is attached to the whole arrangement. Further, the heat in the battery cells is transferred through single cold plate and is discharged. This method is very effective in maintaining the equal temperature at the cell level by readjusting the generated heat flux in the fuel cell equally through fins and highly conductive thermal liquid. But the main limitation of the fin cooling method is that as the liquid is flowing in a single coolant and is cooled with the help of front fins only, the performance of this method decreases slowly as the temperature difference between the liquid and the fin used is slowly deceased.

Type 2 - Mini-channel cold plate cooling method:

Here, the highly thermally conductive mini-channel cold plate is inserted between the cells. Here the temperature is uniformly distributed in between the cells as the liquid is continuously flowing into the mini-channel cold plates. So, the temperature uniformity in the cell is very uniform compared to the fin cooling method. But the main limitation of this method is that it needs a long and narrow channel that results in the high-pressure drop, this can be overcome by using an electric coolant pump with the inbuilt characteristics of having high flow rates and static pressure. Li et al. [23] proposed the design of the mini-channel cooling system using computational fluid dynamics analysis, the design of experiments and selection of surrogate models, formulation of the optimization model, and multi-objective optimization for selection of the optimum scheme for mini-channel cooling based BTMS.



(a) Fin cooling (b) Mini channel cold plate cooling

Figure 5 Secondary loop liquid cooling system in the battery module.

5.3. Liquid cooling

Liquid cooling is another commonly used method for the cooling of LIBs. Compared with air cooling, liquid cooling is more efficient due to higher heat transfer coefficient of water. Liquid cooling can be classified into direct cooling and indirect cooling. Direct cooling (such as liquid immersion cooling) can cool the entire battery surface, which greatly contributes to the temperature uniformity of LIBs. Direct contact liquid cooling [24] is not common in automobile battery cooling system due to its high requirement on the waterproof performance of battery system, and electrical short circuit and electrochemical reaction may occur. Indirect liquid cooling (such as tube cooling, cold plate cooling with mini/micro channels, jacket cooling, etc.) has attracted the attention of many scholars due to its advantages of easier implementation and higher safety. The liquid cooling devices of cylindrical LIB [25] and plate LIB have been proposed and studied. Usually, the cooling device is developed to be compact and light, and new materials [26] are used to improve the cooling channel.

Preheating is also used for liquid cooling. In addition, liquid cooling can also be combined with other methods such as air cooling or heat pipes [27] to create better results. At present, most of the researches focus on the optimization of cooling plates through simulation or experimental methods.

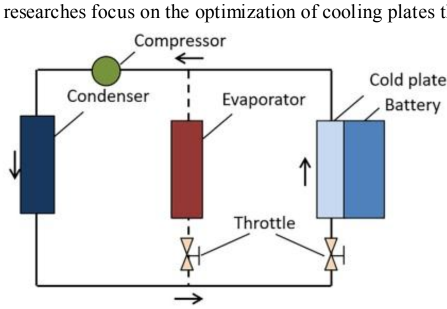


Figure 6 Schematic of liquid cooling

6.3. Phase change material (PCM)

Generally, air or liquid cooling is used for controlling the temperature of a battery system. However, these methods are expensive and have higher operating cost, since it consumes power and electricity. So, a phase change material could be an interesting alternative with a passive or semi-passive thermal management system. These materials can store thermal energy reversibly in latent as well as sensible form [28].

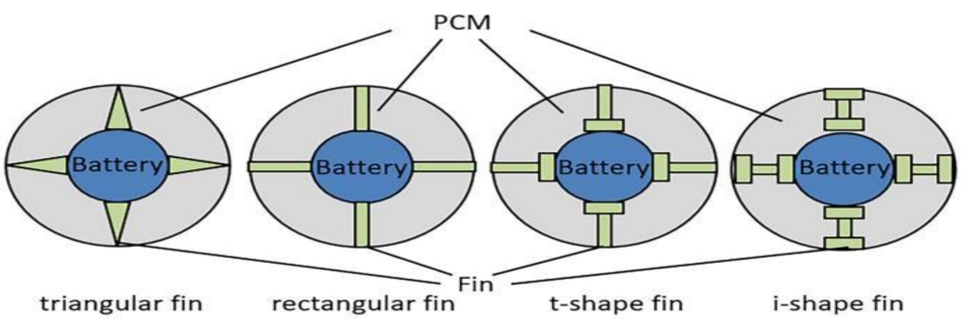
6.3.1. Classification of PCM

The classification of PCM can be done in four categories known as solid-solid PCMs, solid-liquid PCMs, solid-gas PCMs, liquid-gas PCMs. Further solid-liquid PCMs are classified into organic, inorganic and eutectic PCMs. A compound containing carbon is an organic compound whose melting temperature and latent heat vary directly with the extent of the chain. They are produced in the petrochemical industry. In Inorganic PCMs, the compound contains one or more metallic atoms whereas eutectic PCMs are a combination of the above two.

Among all these, paraffin waxes are used mostly since they have high latent heat and possess a wide range of melting temperature. But the main disadvantage of using paraffin is their low thermal conductivity [29].

Furthermore, fatty acids also show a promising performance with a melting range of 30°C to 65℃ and latent heat of 153 to 182 kJ/kg [30]. In inorganic PCM, Hydrated salts have high thermal conductivity compared to paraffin waxes. Also, it is cheaper with high latent heat storage capability. But phase segregation and supercooling limit its use to a different application. This may cause the irreversibility and thus there is a definite decrease in storage capacity over the period. To tackle the above issue some researchers have performed an investigation on hydrated salt [31]. Metal-Laser-Sintered aluminium heat exchangers on the temperature uniformity of battery. PCM cooling can also be combined with liquid cooling or heat pipes to achieve better cooling performance. Bai et al. [34] have designed the PCM/water-cooled plate battery module from the perspective of energy saving and fluid mechanics. The factors that affect the performance of the cooling module, such as the mass flow and flow direction of the inlet, thermal conductivity, PCM melting point, were analysed numerically. The results showed that the PCM/water-cooled plate structure could effectively cool the LIBs. The average battery temperature could be maintained at 38.5^0C. But there was still a temperature difference of more than 10 ^{0}C inside the battery pack. Yu et al. have proposed a BTMS using PCMs and cooling water as the cooling device to control the temperature of LIBs. Specially, the graphite sheets were adopted to improve the thermal conductivity of the PCMs, leading to a better temperature uniformity. The effectiveness of this BTMS was verified by a 3D numerical simulation of LIB module. The maximum temperature difference could meet the demand only when 3 water cooling tubes worked together. A temperature difference of 6-8 ^{0}C still existed at both ends of the battery pack.

A battery pack was formed by two LIBs connected in parallel, and a sintered copper-water heat pipe was sandwiched between them. The battery pack was placed in an acrylic box and the chamber was filled with PCM. The battery heat generated during the day would be stored in the PCM. When the battery temperature continued to rise, the battery heat would be transferred via a heat pipe from battery surfaces to its condensation end, and the water spray was carried out intermittently. When the temperature was cold at night, the latent heat stored in the PCM would be released, protecting LIB from low-temperature degradation in its performance and damages in its materials. The method could significantly improve the working temperature environment of LIBs, but the cooperation of multiple systems made the structure of the LIBs huge and complex.



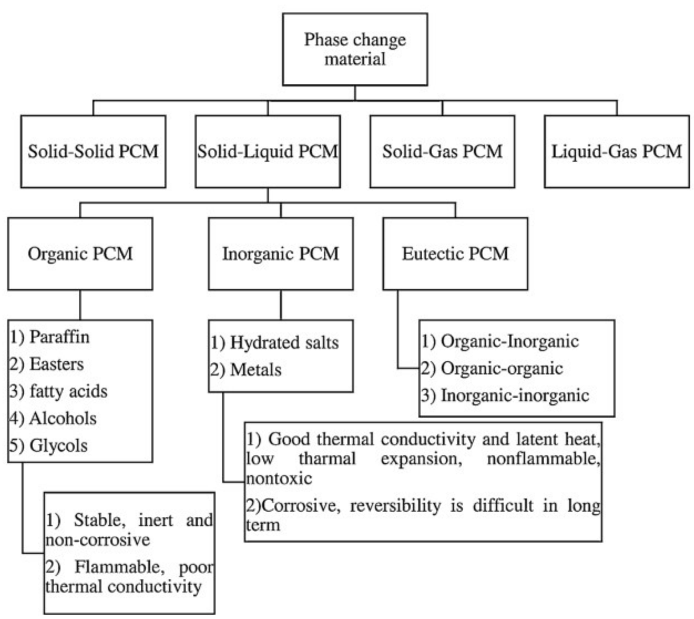


Figure 7 Classification of PCM

6.3.2 PCM cooling

PCM cooling method is similar to that of heating LIBs. Appropriate PCMs should be selected according to different requirements of phase change temperature. PCMs have the advantage of requiring no extra energy and the disadvantages of relatively complex cooling structures. The storage device of PCMs is also the research focus. Choudhari et al. [32] have studied the influence of fin structure on the temperature uniformity of cylindrical LIBs. Simulation results showed that the i-shaped fins could have better heat transfer effect. Landini et al. [33] have studied the influence of Direct-

7. Discussion

Throughout the review, it was found that it was difficult to compare each system quantitatively due to the difference in battery type, capacity, charge/discharge rate and other external conditions. Thus, it would be helpful to evaluate several BTMSs under the same conditions to thoroughly understand the thermal characteristics of each system.

In the near future, the demand for electric vehicles will accelerate at a very high rate. Thus, it becomes necessary to find out the solutions for all the problems which may arise during the operation of an electric vehicle. The structure and the operation of a lithium-ion battery are very much complicated. Among various challenges faced by lithium-ion battery some of them can be summarised as follows:

Battery life: Normally we can use the lithium-ion battery for around 500 number of cycles. After this there is a definite need for battery replacement, so ultimately it will add to the recurring cost. Since, at present, only less than 3% of lithium-ion batteries are getting re cycled from total production. At the same, this battery life also gets affected by the degradation of various components of a battery.

Such degradation is due to multiple side reactions that take place during the operation of a battery. The evolution of such side reactions mainly depends on the design and utilization of a battery.

Operating conditions: The performance of the battery mainly depends on C-rate, maximum temperature, temperature uniformity. Batteries can work efficiently when maximum temperature and temperature differences are within 15℃-40℃ and 5℃ with a C-rate up to 2C. Such conditions are difficult to maintain due to varying loads and ambient conditions at different locations.

Cost: The cost of the battery has to play the most significant role in selecting the battery technology in Electric Vehicles. It mainly includes manufacturing costs and material expenses. The cost associated with each kWh in a lithium-ion battery is about $ (300-600). This value may vary according to the production volume and may get reduced shortly due to rapidly increasing demand.

Environmental impact: Disposal of battery is one of the major challenges in battery technology. Because it not only increases environmental pollution but also valuable resources like cobalt, nickel, etc. are invested in it which is not recycled. Although in the conventional recycling method, deep screening or alkali leaching were used but these processes are hazardous to the environment [35].

8. Conclusions

This paper provides an overview on BTMS focussing on enhancing the thermal performance of the battery with selection and incorporation of a suitable BTMS. Following points have been discussed in detail:

Parameters to design the basic BTMS using mathematical/numerical modelling and simulation

Need of design optimization for an efficient BTMS in an electric vehicle

Air-based thermal management systems such as natural or forced-air cooling hinder the heat dissipation among the batteries due to their relatively low thermal conductivity and heat transferring efficiency

Liquid-based thermal management systems such as heat pipe or fluid liquid cooling need complex structures that increase the cost, and easily causes short circuit if leakage of the liquid occurs in the system and can lead to serious thermal runaway problem for the battery module

Phase change material-based thermal management system affect the weight of battery module incrementally and its cost is extremely high and the instant performance of heat dissipation is also challenging.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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