A Detailed Review on Electric Vehicles Battery Thermal Management System

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Abstract Conventional fuels operated an internal combustion engines are the major sources of carbon emissions and it causes environmental degradation. Electric Vehicles (EVs) offers best efficient and cost effective solution for the above said issue, if the battery charging done by renewable energy conversion base routes when compared to conventional based route. EVs are using lithium-ion batteries for energy storage and it have many challenges like low efficiency at low and high temperatures, decline of electrode’s life at high temperature and safety concerns related to thermal runaway in lithium-ion batteries are the directly impact on performance, reliability, cost and safety of the vehicle. Overheating caused by electron’s movements during chemical reactions during the charging and discharging process in elevated temperatures can lead to fatal destruction of the batteries. Hence an efficient battery thermal management system (BTMS) is one of the most necessary technologies for success of the electric vehicles in the long term. Hence, in this review paper, various types of battery thermal management system along with opportunities for advancement are reviewed. It is concluded that there is a lot of scope for future research in the BTMS for electric vehicles.

1. Introduction

Electric vehicles (EVs) are preferred Lithium-ion batteries for energy storage on its technical features. The higher cost, low discharge rate, long life cycle, and limited energy density of the currently available li-ion battery results in low efficiency to overcome these issues at their fullest capacity [1]. The performance of EVs is highly reliant on the battery capacity and its core temperature plays a major role in battery performance. Wan et al [2] studied thermal performance of a miniature loop heat pipe using water-copper nanofluid. Mochizuki et al (2014) studied Heat pipe-based passive emergency core cooling system for safe shutdown of a nuclear power reactor. Zhao et al [3] reviewed the thermal performance improving methods of lithium-ion battery electrode modification and thermal management system. The battery temperature has a strong effect on charging and discharging rate of the battery. This makes the thermal management of an EV battery pack extremely important, design of energy-dense packs have to employ robust cooling systems, often using liquid cooling loops with hundreds of channels. The complexity of these systems adds to the cost – somewhere around 10-20% of the overall cost of the battery pack. Li-ion batteries are particularly susceptible to thermal run away events for a few different reasons, including their high energy content and their propensity to self-heat once the electrolyte reaches a certain temperature (from 70°C to 130°C). Li-Ion cells are naturally subjected to deterioration with time due to their operating conditions and state of charge. Temperature has a major impact on the efficiency of nearly all batteries [4]. Due to popularity of rapid charging and performance driving, the heat losses in the cell increases due to high current in the cells [4]. There are two main sources of heat generation in a battery cell: electrochemical operation and joule heating due to the motion of electrons within a battery cells. The temperature range of 25°C to 40°C provides the ideal working conditions for Li-ion batteries and if the temperature is elevated above 50°C it becomes...
harmful for the lifespan of the batteries:. Even a single cell’s immature deterioration can reduce the performance and efficiency of the whole battery pack considerably. The main aim of the BTMS is to regulate the temperature of the cells of the battery and thereby increase the lifespan of the battery. There are two main types of BTMS: active systems and passive systems. The active system mainly depends on forced circulation of a specific coolant such as water or air. A passive system uses methods like heat pipes, hydrogels, and phase change materials to have zero power consumption and thus improves the net efficiency of the vehicle. In this paper, a detailed comprehensive of BTMS are reviewed from the available works of the literature along with research for further development is highlighted. Also, the challenges and opportunities for future research are addressed.

2. Batteries thermal management system

The basic types of BTMS are listed below.

1. Air cooling
2. Liquid cooling
3. Direct refrigerant cooling
4. Phase change material cooling
5. Thermoelectric cooling
6. Heat pipe cooling

2.1. Air cooling

Air systems use air as the thermal medium. The intake air could be direct either from the atmosphere or from the cabin and could also be conditioned air after a heater or evaporator of an air conditioner. The former is called a passive air system and the latter is an active air system. Active systems can offer additional cooling or heating power. A passive system can offer some hundreds of watts cooling or heating power and active system power is limited to 1 kW [5]. Because in both cases the air is supplied by a blower, they are also called forced air systems.

Note that the air system offers full functions of heating, cooling, and ventilation. There is no need to build an additional ventilator, but it must be noted that the exhaust air cannot be returned to the cabin again. In some cases, a heat recovery unit (air-air heat exchanger) is mounted after the battery pack to recovery the heat from the exhaust air. It can prevent the mixture of exhaust air with intake air and at the same time provide extra saving potential.
2.2. Liquid cooling

It is a cooling system in which water is used as the coolant for the purpose of cooling the battery. Liquid cooling is the most commonly used cooling system due to its convenient design and good cooling performance. Dielectric liquid cooling or direct-contact liquid which can contact the battery cells directly, such as mineral oil. The other is conducting liquid or indirect-contact liquid which can only contact the battery cells indirectly, such as a mixture of ethylene glycol and water. Depending on the different liquids, different layouts are designed. For direct-contact liquid, the normal layout is to submerge modules in mineral oil. For indirect-contact liquid, a possible layout can be either a jacket around the battery module, discrete tubing around each module, placing the battery modules on a cooling/heating plate or combining the battery module with cooling/heating fins and plates [7]. Between these two groups, indirect contact systems are preferred to achieve better isolation between the battery module and surroundings and thus better safety performance. The studies on the liquid cooling system have always been fixated at the development of the physical design of the cooling plate and its channels and by targeting the parameters like; coolant pressure drop across the channels of the cooling plates and cell core temperature different designs are fabricated. According to the previous research on the geometric development of the cooling plate, the highest cooling performance was achieved by channelled cooling and it also showed the minimum power consumption as compared to other methods. But channelled cooling is not ideal for temperature consistency due to the comparatively long path of flow.

The path of the heat transfer from the bottom of the battery to the cooling plate highly contribute to the thermal resistance of the battery pack structure, several modified pack designs are devised to enhance the cooling performance such as Thickened cooling fin design, Sandwich cooling plate design and the Interspersed cooling plate design. To optimize the structural design of the practical and large scale battery thermal management system for electric vehicles. A thermal model for the indirect fin-cooling battery pack is developed, type D-2 was proposed as an alternative design for BTMS. It improved the ratio of equivalent heat conductance to the system volume by 64% and the total pressure drop is increased by 19% and the maximum temperature difference was reduced by 5.4°C [8].
2.3. Direct Refrigerant cooling

Similar to active liquid systems, a direct refrigerant system (DRS) consists of an Air Conditioning loop, but Direct Refrigerant System uses refrigerant directly as heat transfer fluid circulating throughout the battery pack.

2.4. Phase Change Material

Phase change material absorbs heat throughout the melting process and saves it as latent heat till it reaches a maximum value. For a period, the temperature is kept at a melting point and then the temperature increase is delayed. Therefore, PCM is used as a conductor and buffer in the BTMS. Also, the PCM is always combined with another BTMS system such as liquid cooling or air cooling system to manage the battery core temperature.
2.5. Thermoelectric cooling

To improve the cooling/heating power of passive air systems, there are two possible upgrades. One is through thermo-electric modules. The thermoelectric cooling system changes the electric voltage into temperature difference and vice-versa. In this paper, the change of electric voltage onto temperature is discussed. It removes heat through the components by exhausting electricity directly. Fans are equipped to improve heat transfer by forced convection. To blend a passive air system with the thermoelectric system and the connected system cools down the battery temperature even less than the input air temperature, and the power is limited to less than one kW [5]. It allows with the ability to switch between cooling and heating operations and to do that only the polarity of the electrodes is needed to be reversed.

2.6. Heat pipe cooling

It’s a passive cooling system which is basically a sealed tube filled with refrigerant and it absorbs heat by vaporizing the refrigerant from the hot side and it removes heat into surrounding by condensing the refrigerant back to liquid, form on the cold side and then flows back. A partial vacuum is maintained in the casing of the heat pipe and to increase the heat transfer rate of heat pipes a capillary structure is used within the heat pipes which increases the surface temperature. The heat pipe may use water or any refrigerant as the coolant and this cycle repeats again and again. The battery acts as a heat source and sits below the heat pipe (on the evaporating side) and the cooling fins acts as the heat sinks on the heat pipe (on the condensing side). According to experiments, a reduction of 30% in the thermal resistance is found for heat pipe cooling system under natural convection as compared to without heat pipe. A thermal resistance reduction of 20% under low air velocity convection is possible. The main problem with this cooling is the safety of the system which can be a concern in the case of an emergency; a short circuit can happen due to the coolant leakage on the battery cells which can cause a failure of the vehicle and can be fatal. Also, the capillary tubes require a minimum diameter to maintain an adequate pressure drop and avoid blockage.
3. Existing Battery Thermal Management System

The most commonly used BTMS is the liquid cooling system which provides a compact design and a high cooling performance. The mainly used coolant in liquid cooling system is water due to its easy availability and low cost, but the possibility of an electric short is a huge problem in this system. So to overcome this indirect cooling system is used by many dominant electric vehicles manufacturers. Also, the liquid cooling system has always been fixated at the development of the physical design of the cooling plate and its channels and also by targeting the parameters like; coolant pressure drop and cell core temperature we can achieve the best design for a liquid cooling system.

3.1. Heat Pipe Battery Thermal Management System

Due to consumer demands the driving range of the vehicle has to be increased which then causes to increase the size of the battery which then makes the generation of the heat a serious issue in the battery due to which a great BTMS becomes a basic necessity? An efficient BTMS must be able to perform its operations safely and heavily in the space present within the vehicle, and it must be able to provide the necessary heat transfer, along with the ability to be manufactured economically. In these constraints, the heat pipe cooling system
will prove to be a best solution for our problem due to its high temperature uniformity, portable size and low weight.

![Heat pipe based thermal management system assembly.](image)

**Figure 7.** Heat pipe based thermal management system assembly.

along with its superior cooling performance and it also has a past usage history in the electronic industry. The heat transfer rate for a heat pipe is higher as compared to a solid metal rod of the same size, and also there are no moving parts in this system. In a well-arranged heat pipe cooling system, the thermal performance can be assured of high level and independent of the orientation of the heat pipes [11] and also it is a passive system and does not drain any energy from the battery so the overall efficiency of the battery is not affected [12]. Also by developing the flow properties of the wick such as pore size, porosity, permeability, working fluid's type and charging ratio the most of the structural and operational needs for a heat pipe cooling system can be solved along with the assembly process such as coating process, tying or locking technology and assimilation principle.

There are three basic elements in the heat pipe BTMS:

1. **Heat extraction unit:** It is used to provide thermal control at the cell-level and it consists of heat pipe cooling plates to maintain temperature uniformity in the cells and to transfer the heat from the cells to an external plate.
2. **Heat transmission unit:** It is used to transmit the heat away from the battery and the heat pipes are used to transfer heat from the external plate to a remotely located liquid cooling system.
3. **Heat dissipation unit:** It is used to provide a thermal control over the whole cold plates to transmit the heat away from the battery and the electronics of the system to the coolant of the heat pipes which then transfers the heat to the radiator.

3.2. **Thermal Modelling of cooling system**

The chemical reaction in the Li-ion cells generates heat and this joule heat is transmitted from between the cells to the heat pipe cooling plate with the help of coolant, which is used to transfer the heat from the cells to the heat pipe cooling plate. Then this heat is transmitted through heat pipes to the contact plate, and then the combined heat of the cooling plate and contact plate is transferred to the remote heat transfer heat pipes. And then the heat is transmitted remotely to the second contact plate by the remote heat transfer heat pipes,
which is then connected to the liquid-cooled cold plates. Cold plates transmit heat by forced convection of cooling water through the micro-channels. Water is mainly used as a coolant because it has exceptional thermal properties and high heat transfer coefficient. The net thermal resistance of the heat pipe-based BTMS can be divided into 3 types of thermal resistance: contact resistance, heat pipe resistance and the forced convection resistance of the cold plates.

Thermal Contact Resistance

Contact resistance of the cell contact is calculated by

\[ R_c = \frac{t_c}{k_c A_c} \]  

Where \( k_c \) is the thermal conductivity of the contact material, \( t_c \) is the temperature of the cell and \( A_c \) the surface area which is in contact.

Due to limited contact area and high flatness tolerance between the heat pipe and metal plates, a high conductive interface is created by using soldering. And if the parts in the contact have the same contact areas, and only a minimum spreading is involved then we can conclude that there is approximately one-dimensional heat transfer which can be estimated from Equation (a).

Thermal Heat pipe resistance

Thermal resistance in the heat pipe emerges from the heating and cooling process and is calculated from the equation (b)

\[ R_{hp} = \frac{1}{h_{cd} A_{cd}} + \frac{1}{h_{ev} A_{ev}} \]  

Where \( h_{cd} \) and \( h_{ev} \) are heat transfer coefficients for condensation and evaporation process, and \( A_{cd} \) and \( A_{ev} \) are the surface areas of the condenser and evaporator respectively (Incropera et al. 2002).

Thermal Cold plate resistance

Due to forced convection, the cold plate heat transfer coefficient \( h_{cp} \) and heat transfer area \( A_{cp} \) play a vital role for the thermal resistance from the base of the cold plate to coolant and it is calculated using Equation (c).

\[ R_{cp} = \frac{1}{h_{cp} A_{cp}} \]  

The heat transfer coefficient \( h_{cp} \) of the forced convection depends on the capillary tube characteristics such as aspects ratio, thickness and coolant flow circumstances like fluid velocity and flow configuration along with other coolant properties which can be calculated using Nusselt correlation [3]. A heat pipe BTMS was proposed by the studies of (Smith et al 2018) which consists of heat pipe cooling plates to extract heat from individual cells, a remote heat pipe module to transport heat up to 300mm distance, and liquid cold plates to dissipate heat from heat pipe system to ambient air.
4. Comparison of existing v/s proposed battery thermal management system

The existing BTMS utilizes a liquid cold plate attached at the foot of the cell for heat dissipation. It has an overall cooling system with 8 cold plates connected in series, mechanical pump to circulate liquid through the cooling loop and remotely located radiator to remove heat from the coolant. This is an active system and utilizes the power from the batteries to remove the heat from the coolant and thus reduces the overall efficiency and performance of the battery pack. The proposed cooling system is a heat pipe system the heat pipe cooling system will prove to be a best solution for our problem due to its high temperature uniformity, portable size, low weight along with its superior cooling performance and it also has a past usage history in the electronic industry. The heat transfer rate for a heat pipe is higher as compared to a solid metal rod of the same size, and also there are no moving parts in this system. In a well-arranged heat pipe cooling system, the thermal performance can be assured of high level and independent of the orientation of the heat pipes [11, 12].

5. Opportunities for Advancement

The advancements in the batteries can be achieved by improving the design of the electrode and battery capacity by reviewing the design, size, and types of materials used for the construction of the battery. The reaction between chemicals takes place at the electrode and by reducing the internal resistance of the electrodes it is possible to decrease the amount of heat generated and therefore increasing the cell capacity and lifespan. By reducing the size of electrodes, the efficiency increases as noted [13] in their research but there is a limit to which the electrode size can be reduced and if the thickness of the electrode fell below 130 µm then the battery was no longer able to meet the needed energy demands and there are also additional tradeoffs with the thinner material size including increased cost of manufacturing. Electrode size can be included as a key design factor in the overall design of the entire system. Construction of the electrodes by modifying the material as they produced, it is possible to optimize the transport distances or route of the ion travel to improve the overall conductivity and thermal performance [3].

6. Conclusion

The rapid usage of the EV is going to increase in the near future as sustainable transport is concerned and due to which the need for development of an efficient batteries are priority. The thermal losses of the batteries are main challenges to develop better BTMS. The range and work load of the EV is going to increase. This paper gives review report of various BTMS and opportunities for future work are highlighted.

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