Retraction

Retraction: A review on passive cooling techniques for lithium-ion battery thermal management system of electric vehicle (IOP Conf. Ser.: Mater. Sci. Eng. 1145 012046)

Published 23 February 2022

This article (and all articles in the proceedings volume relating to the same conference) has been retracted by IOP Publishing following an extensive investigation in line with the COPE guidelines. This investigation has uncovered evidence of systematic manipulation of the publication process and considerable citation manipulation.

IOP Publishing respectfully requests that readers consider all work within this volume potentially unreliable, as the volume has not been through a credible peer review process.

IOP Publishing regrets that our usual quality checks did not identify these issues before publication, and have since put additional measures in place to try to prevent these issues from reoccurring. IOP Publishing wishes to credit anonymous whistleblowers and the Problematic Paper Screener [1] for bringing some of the above issues to our attention, prompting us to investigate further.

[1] Cabanac G, Labbé C and Magazinov A 2021 arXiv:2107.06751v1

Retraction published: 23 February 2022
A review on passive cooling techniques for lithium-ion battery thermal management system of electric vehicle

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Abstract. Li ion batteries have gained popularity in electric vehicle application in past few years because of its high energy density and long-life cycle. The high energy density Li ion batteries are also generating a large amount of heat which needs to be dissipated for the stability, longevity of the battery and safety of vehicle. Thus, a battery thermal management system (BTMS) is very much essential for the battery system. The objective of BTMS is to maintain the cell temperature and thus improve life cycle of battery system. It has been reported that the battery pack has better thermal stability and lifetime when operated at a temperature range of 15 to 35 °C and maximum cell temperature difference of 5 °C. Among battery cooling techniques, passive approaches are considered as less complex and less expensive. In this context, a review on passive cooling methods for BTMS has been discussed in this paper. Subsequently, a summary of characteristic parameter for an efficient passive BTMS has been provided.

1. Introduction
Humans are always in quest for new, advanced technologies and so is the automobile sector. With the growth of automobile industry, dependence on fossil fuel, climate change and environmental issues are increasing every year. To address these issues, the automobile sector is now looking for a cost effective, safe, and reliable battery or battery-powered electric vehicles. Electric mobility is seen to be expanding at a rapid pace, globally. The sales of electric cars have been increased to 94% worldwide between 2011 to 2015. In 2018, the worldwide sales of the electric cars surpass 5.1 million, which is 2 million higher from the previous year. The sales of electric vehicles in Europe, China, and the United States of America have majorly contributed to the growth of electric mobility.

The energy efficient clean vehicles like the pure Electric Vehicles (EVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Hybrid Electric Vehicles (HEVs) uses various kinds of batteries as power source. Different characteristics that a battery of an Electric Vehicle includes are high performance, low initial cost, adequate mileage per charge, low maintenance cost, long life cycle, materials recyclability, operational safety, low self-discharge and zero pollution to name a few. There are various types of batteries used in Electric Vehicles, namely Lead Acid, Lead gel, Nickel-Cadmium, Nickel-Metal hydride, Lithium based batteries etc. Among the different types of batteries, the rechargeable Li-ion batteries have been considered as the most suitable battery for electric vehicles due to its higher specific power, higher energy density, lower self-discharge rates, lighter weight, enhanced life cycle and no memory effect as compared to other energy storage systems like nickel-
cadmium or lead-acid batteries. A high-performance Li-ion battery is useful in various applications like electric vehicles, smart grids, high energy power sources. Li-ion battery has become the most useful in various applications as the other methods of energy storage like flow battery, zinc-air battery, lithium sulphur battery, fuel cells, graphene based electrochemical micro supercapacitors are in the stage of laboratory research till now.

Operating and ambient temperatures of the battery plays a vital role on performance of the Li ion battery. The battery temperature influences the electrochemical operation of the battery such as charge acceptance, power and energy capability, life, reliability and round-trip efficiency. The degree of capacity fade also increases with the increase in temperature. The excessive heat generated in the batteries have negative thermal effects on battery lifecycle and operational safety which includes thermal runaway, capacity fade or capacity loss, low performance, and electrical imbalance between the different cells in a battery pack. Li ion cells cycled with a Current of higher than 2C experiences a temperature beyond 38 °C inside the cell. During short circuit of a Li-ion battery, high amount of electricity flows and within seconds temperature of the battery increases to several hundred degrees in turn heating up the neighbouring cells which may damage the whole battery pack. During unintentional overcharging of the battery, Li ions forms snowflake like structures of Li metal deposits, called dendrites which causes short circuit in the battery and can cause explosion and fire in the worst-case scenario. High temperature in battery pack reduces energy efficiency, disrupts the electrochemical operation, affects safety and reliability, extends charging time, shortens the life span and requires maintenance.

The performance of Li-ion batteries decreases because of loss of capacity and/or rise in the temperature. [1] showed in their study with the help of half-cell diagnostics that anode did not lose much capacity, but the capacity of the cathode decreases significantly after the cell is cycled at 60 °C. The degradation in battery capacity of vehicle is characterized by a loss in vehicle performance, if the heat generated in the battery during charging/discharging is not released.

Heat is generated during the charging and discharging cycles of Li-ion cells are because of various thermo-physical and chemical reasons. The three main reasons of heat generation in Li-ion batteries are: Ohmic Joule heating from the movement of charged particles, concentration of species transport and activation of interfacial kinetics. Total heat generated can be calculated by equation (1)

$$\dot{Q} = I (U - V - T \frac{dT}{dt})$$

(1)

Where $\dot{Q}$ is the rate of heat generation, $I$ is the current drawn, and $U$ and $V$ are open circuit voltage of the battery and cell voltage respectively. It is noted that stressful conditions like defects in individual cells as well as high amount of power extraction at high temperature may cause severe heating of the battery. Factors like high discharge rate and regenerative braking also contributes to the steep rise of temperature within the cell. Table 1 shows the Capacity fade in Lithium-ion batteries.

| Cathode/anode  | Voltage(V) | Discharge rate | Temperature Operating Cycles | Capacity fade (%) |
|----------------|------------|----------------|-------------------------------|-------------------|
| C/LiCoO2[22]  | 4.2-2.5    | 1C             | 21                            | 9                 |
| C/LiMnO4      |            | 45             | 500                           | 28                |
|                |            | 21             |                               |                   |
| C/LiCoO2[23]  | 2.4-2.2    | 1/9C-1C        | 25                            | 6.09              |
|                |            | 55             | 150                           | 9.4               |

Table 1. Capacity fade in Lithium-ion batteries.
Again, when the temperature of a cell crosses a certain limit, a series of undesired chemical reactions happens inside the cell which trigger further increase in temperature of the cell as well as of the whole pack. The reaction and rise in temperature continue until it catches fire if not controlled. This abnormal behavior is called thermal runaway. Thermal Runaway is initiated at about 90 °C in Li ion cells and can occur due to various reasons like overheating, overcharging, nail penetration, and short circuiting. The life and thermal stability of battery pack improves when operated within 15 to 35 °C cell temperature and maximum 5 °C cell temperature difference.

2. Battery thermal management system (BTMS)

BTMS is a part of Battery Management System which have necessary hardware and software components to maintain the temperature of whole battery module in optimal range and thereby optimize the battery pack lifecycle, safety, and stability in operation. It should be noted while designing a battery pack that the heat generated must be drained out quickly so that the battery must not reach the thermal runaway temperature. At thermal runaway temperature, irreversible decomposition of the battery components activates an exothermic chain reaction which results the desolation of the battery. The designed BTMS should have the following characteristics i.e., compact, lightweight, reliable, easy-to-assemble, placed in appropriate position, and cost effective in addition to being able to efficiently dissipate heat from the battery pack. Apart from this, to have a state-of-the-art system, the BTMS should be efficient and simple to operate. The BTMS can be used to either cool, heat or insulate the battery pack depending on the operating and ambient conditions. Also, subjecting to the location of the stack or the system and the ambient temperature, the heating or cooling method employed can create non-uniform distribution of temperature in the battery pack. At high charging and discharging scenario, the thermal management system must remove heat quickly and maintain the cell temperature uniformly, otherwise it could lead to unbalance of the whole system.

2.1. Types of BTMS

The different techniques that are employed in a BTMS are use of extended surfaces, immersion cooling, cold plates, thermoelectric coolers, use of phase change material and heat pipes. Designing Battery Thermal Management System can be classified into following categories:

1. Active Methods and
2. Passive Methods

Active Methods use external power for its operation. A built-in source helps in the operation of heating and/or cooling. The Active management methods include air cooled, water cooled and thermoelectric cooled techniques. Air Cooled methods employed by Fan/blower whereas water
cooling methods is employed by cold plates, Cooling tubes and Immersion techniques. Figure 1 shows the types of BTMS.

Figure 1. Types of BTMS

3. Passive battery thermal management system
Passive BTMS do not require any external power supply for its operation. It uses the ambient environment to dissipate the heat. As they do not need any external power source, they are the most sought methods in the field of developing a thermal management system. These methods also have the advantages of being compact, less complex, safe, cost efficient and enhanced-life cycle.

Passive BTMS in application of EVs includes use of extended surfaces, PCMs, Heat Pipes and combination of two or more methods. Phase change materials have higher amount of latent heat of fusion due to which it absorbs a large amount of heat energy till the phase of the material is changed from solid to liquid. Heat pipes are a type of heat exchangers tube made of copper which has the advantage of very high thermal conductivity, light weight, compact in size. Therefore, these two are mostly used individually or in combination as passive cooling methods in thermal management systems.

3.1. BTMS using PCM
In application of thermal management in EVs, PCMs are applied to the surface of battery cells. PCM surrounded to battery module starts to melt when the battery temperature surpasses the PCM phase change temperature. During the melting process, it absorbs the heat dissipated from the battery module by undergoing phase transition from solid to liquid. This helps to prevent sharp rise in the temperature of the battery module. Advantages of PCM are its high number of charging-discharging cycles, high storage density, and isothermal nature of phase change temperature. Also, PCM can store the dissipated heat over a narrow range of temperature. Latent heat is used instead of sensible heat because of reduction in thermal energy storage, thermal inertia and high efficiency of heat transfer for a small difference of temperature. In comparison to other cooling systems, the battery packs having PCM provide compactness and helps in reduction of weight of the large power systems. During the selection of a PCM the main parameters are latent heat of fusion and melting temperature. PCM should have high enough melting point temperature and latent heat of fusion.
Table 2. Paraffin’s thermo-physical properties

| Properties               | Paraffin Wax |
|--------------------------|--------------|
|                         | Melted       | Solid        |
| Density, kg/m³           | 822          | 910          |
| Melting Temperature, °C  | 56           | -            |
| Specific heat, J/kgK     | 1770         | 1770         |
| Thermal conductivity, W/m-K | 0.21      | 0.29         |
| Latent heat of fusion, kJ/kg | 195        |              |

3.1.1. Pure Paraffin as PCM

Paraffins wax is one of the most preferred phase change material due to its low cost, low corrosive nature, easy availability and high latent heats. For the first time, Paraffin as PCM in thermal management of EVs battery was reported by [2]. They performed a simulation study on battery module of eight 100Ah cylindrical cells using PDEase2D, a commercial 2D finite-element method tool. They reported a very good improvement in battery performance i.e 30-40% improvement due to thermal management of the module. Thermo-physical properties of the pure paraffin considered during the study are shown in Table 2. Latent heat of fusion and melting temperature are two decisive parameters in selection of PCMs. The battery thermal management at both higher and lower ambient temperature can be improved by higher latent heat storage capacity of paraffin wax. [3] studied the melting temperature influence on battery performance with paraffin of phase change temperature of 36°C, 44°C and 52°C. It was reported that paraffin at a phase change temperature range of 40-45°C gives optimum cooling performance. [3,4] compared paraffin of melting temperature 36°C, 45°C and 58°C and concluded that PCM of 45°C with melting temperature and 111.3 kJ/kg latent heat shows minimum surface temperature difference and lowest surface temperature. PCM having melting temperature of 36°C had the lowest amount of latent heat, therefore it absorbed all the latent heat and could not dissipate excess heat from the module. While PCM with melting temperature of 58°C could not reach its melting point during operation hence latent heat could not be utilized.

Along with various advantages, paraffin has some disadvantages as well. Low thermal conductivity is one of the main disadvantages. This drawback can be overcome by using various methods such as usage of multiple PCMs, incorporating extended surfaces, PCM encapsulation, embedding metal additives within the PCM, inserting PCM into a metallic matrix, and impregnating porous graphite matrix into the PCM etc.

3.1.2. PCMs with enhanced thermal conductivity

3.1.2.1 PCMs with Fins

Extended surfaces or fins are attached to the battery module and PCM which increases the area of heat transfer and improves thermal efficiency. There are two ways in which the fins are installed; One is into the PCM and the other is over the surface. Previous studies suggested that the heat dissipation rate from the surface using fins is influenced by structure, material, number, and other parameters. [4] investigated the effect of fins at the top and bottom surfaces of the battery module. The heat dissipation from the battery module was found to increase with fin addition. There was a temperature reduction of 11%, 33%, and 43.8% for the discharge rate of 1C, 2.5C and 3.5C respectively. The PCM used in the experiment was a composite of paraffin, EG and polyethylene. [5] studied different types of fins, namely longitudinal, rectangular, triangular cross-sectional area and pin fins. Longitudinal fins are suggested to use in case of natural convection heat dissipation and pin fins in case of forced convection. [6] studied the effect of a novel battery module containing longitudinal fins and ring on heat transfer by carrying experiments with 4,8 and 12 number of longitudinal fins on cylindrical
battery prototype. They found that the optimum number of fins for fast heat dissipation is eight because with the increase in surface area of the fin, PCM amount is decreased. [7] studied the phase change time of PCM in an annular structure fitted with fins and metal foams. It is reported that melting time drops by 8% compared to pure PCM when fin length at bottom is increased and similar results were obtained using different metal foams also. The time required for melting initially dropped but later increased with number of fin additions for the same thickness of the fins and volume. Figure 2 shows the PCM thermal conductivity enhancement techniques.

![Figure 2. PCM thermal conductivity enhancement techniques](image)

3.1.2.2 PCM packaging
There are primarily two types of packaging technology of PCM are used in practice namely dispersed packaging and microcapsule packaging. Packaging, where a fixed amount of PCM is added to the container, is called dispersed packaging. Its application is found in energy storage water heaters and residential buildings. Overall heat dissipation can be increased by giving a sturdy polymer coating on PCM surface forming a core-shell PCM structure. This micro encapsulated PCM has two parts: core as PCM and shell as organic or inorganic compounds. [8] reported a good thermal storage capacity of micro encapsulated PCM for n-octadecane which was used as core and CaCO3 being the material of shell. This packaging has a good feasibility because of low-cost material associated with it. [9] used micro encapsulated paraffin as core and a mixture of CaCO3 and expanded graphite as the shell material. Addition of 24% EG by weight in micro encapsulated PCM improved thermal conductivity 24 times in comparison to paraffin.

3.1.2.3 PCM with metal particles
The addition of high thermal conductive nano particles such as nano powder, carbon nanotubes can increase the lower thermal conductivity of paraffin. [10] used PCM composites of pure paraffin, Expanded graphite, graphene, and carbon nanoparticles. They used pure PCM, PCM composite, PCM with copper foam at central and pure PCM in surroundings in their investigation and reported that addition of metal particles can reduce battery temperature by 5-20%. Metal foam addition also improved the uniformity in battery temperature. [11] showed that PCM emulsion containing n-hexadecane resulted in better thermal conductivity when SiO2 nano particles were added. PCM emulsion had better thermal conductivity because of higher fluidity and volume change as compared to solid PCM. [12] prepared PCM composite with Aluminum nitride of various mass fraction of 0.05, 0.1 0.15 ,0.20 and 0.25 and found that composite with 0.2 mass fraction had highest thermal conductivity. The BTMS with composite material was able to reduce maximum battery temperature by 19.4% in comparison to air cooled BTMS. Table 3 shows the Summary thermal enhancement methods of PCM.

Table 3. Summary thermal enhancement methods of PCM
3.1.2.4 PCM with filler materials

Metal foams are light weight porous structure of high mechanical strength with many pores. These pores are either sealed or open. Metal foams of Aluminum, Copper and Nickel are used for enhancement of the thermal conductivity of the PCM. [13] investigated PCM aluminum composite and reported 218 times increase in thermal conductivity which brought 62.5% and 53% decrease in the battery-temperature for 1C and 2C discharge rates respectively. [14] used copper foam and paraffin composite and reported large improvement in thermal conductivity. [15] studied paraffin copper foam composite and Paraffin Nickel composite in battery thermal management. The comparison with pure paraffin shows a great improvement in thermal conductivity for the composite PCM. They found increase of thermal conductivity with reduction of porosity of the metal foam. The most useful and efficient one out of these techniques is the graphite matrix because of its simplicity in manufacturing, high thermal conductivity and its surety in maintaining temperature uniformity within the pack along with high volume and mass fractions of PCM. [16] showed from their study that composite matrix can obtain a thermal conductivity of 20-130 times of that of pure PCM. [17] investigated a model based on different PCM materials and compared them. The study was conducted based on pure paraffin, EG and Paraffin composite and EG, Epoxy and Paraffin composite and concluded that EG, epoxy and Paraffin composite works efficiently for discharge rates of 1C, 3C and 5C and the maximum surface temperature was found to be 59.79 °C. [18] performed numerical analysis of BTMS with n-octadecane permeated within polyurethane. Their study inferred that the wet foam decreased the temperature of

| Author | CPCM | Thermal conductivity (Pure PCM) | Thermal conductivity (CPCM) | Battery load (heat flux) | T<sub>amb</sub> | Maximum Cell Temperature | Maximum Cell Temperature (with CPCM) | % reduction compared to Free convection | % reduction compared to Pure PCM |
|--------|------|--------------------------------|----------------------------|-------------------------|----------------|--------------------------|--------------------------------------|---------------------------------|------------------------------|
| [6]    | Paraffin+EG | 0.2 | 1.72 | 2.5 C | 28 | 61.8 | 47.6 | 47 | 23.95 | 1.26 |
| [7]    | Paraffin wax+Fin | 0.2 | - | 2 C | 25 | 39.6 | 37.9 | 35.1 | 10.69 | 6.59 |
| [8]    | Paraffin wax+ Fin | 0.2 | - | 10 W | 20 | 60.5 | 42.4 | 39.2 | 35.20 | 29.91 |
| [9]    | Paraffin wax\ +graphene+ MWCNT | 0.38 | 0.87 | - | 25 | - | 54 | 46 | - | 14.81 |
| [10]   | Paraffin wax+EG+AlN | 0.2 | 4.331 | 3C | 45 | 59.03 | - | 54.66 | 7.40 | - |
| [11]   | n-Octadecane+Metal foam | 0.255 | - | 5 C | 21 | 69 | - | 59 | 14.49 | - |
| [12]   | Paraffin wax+Cu foam | 0.2 | 11.33 | 1C | 25 | 70 | 55 | 48 | 31.43 | 12.73 |
| [13]   | Paraffin wax+Graphene coated nickel foam | 0.19 | 4.6 | 2.2A | 33 | - | 46 | 43 | - | 6.52 |
the battery by 7.3 °C as compared to that of dry foam. [19] investigated the use of copper foam paraffin composite in BTMS application for 0.5 C, 1C and 3C. The effect of pore density (for 10, 20 and 40 PPI) and porosity (for 0.90, 0.95, and 0.97) and were also studied. Low pore density and porosity were found suitable for thermal management application from the study. [20] reported increase in thermal conductivity of the PCM by 23 times when graphene coatings on nickel foam were employed. This resulted in decrease of battery temperature by nearly 2 °C in comparison to pure paraffin.

3.2. BTMS using heat pipes
Heat pipe is a closed, compact, evacuated tube lined with a porous capillary wick structure on the inner walls where an appropriate amount of fluid is filled inside the tube as working substance. It is a very high thermally conductive heat exchanging device which works on the principles of phase transition of liquid to vapor and vice versa. Heat pipe mainly used for heat exchange between two solid interfaces. When a portion of heat pipe encounters hot environment, the fluid in that portion changes its phase from liquid to vapor and flows to the cooler section. It condenses there by releasing latent heat of condensation then the condensed liquid flows back by capillary action to hotter portion. This cycle continues by maintaining temperature as working fluid changes phase. The heat pipe application is commonly found in computing and electronic devices. It is also used in thermal management system in satellite and space craft systems. Recently researchers have started its application in thermal management module of electric vehicles. Figure 3 shows the heat pipe.

![Figure 3. Schematic diagram of a heat pipe.](image)

BTMS model based on heat pipe and a cold plate arrangement could maintain the temperature below 55 °C and that between the prismatic cells were continued to be in a range of ±5 °C. The model consists of a remote heat pipe module and a cooling plate attached to the condenser section. [21] performed experiment on a 400W cartridge heater as prototype of battery module for three different loads of 0.48, 0.96, and 1.61 W/cm². A flat plate loop heat pipe arrangement made of copper was used with working fluid as alcohol, distilled water and acetone for thermal management. It was concluded that for the heat pipe starting heat flux is below 0.48 W/cm² and while using acetone the temperature limit can be maintained below 50 °C. [22] used a novel wick structure of stainless-steel screen mesh in the evaporator section of copper heat pipe. An ultra-thin heat pipe system for pouch Li ion battery module was studied with wet cooling method. It was concluded that using water sprays, the temperature of a 8Ah battery pack could be maintained below 30 °C and the temperature difference of 1.5 °C across the cells. A heat pipe based BTMS with chimney-based ventilation is investigated by [23]. It was reported that the combined system could improve the heat evacuation from the battery pack. Investigation on a BTMS model based on heat pipe, proposed by [24] concluded that the maximum temperature of the batteries can be kept within 50 °C when the rate of heat generation is below 50W.
3.3. BTMS in combination with two or more passive methods.

The low thermal conductivity of PCM limits its application despite of high latent heat capacity and low cost. In this regard a second component of high thermal conductivity is always incorporated to improve the thermal conductivity property of PCM. The combination of PCM and Heat Pipe is well sought for a fully Passive BTMS. [25] made a comparison between PCM based BTMS, BTMS under natural convection and BTMS coupled with PCM/HP. The difference in the maximum temperature of PCM/HP coupled BTMS was reported below 5 °C for longer duration than the other two. The experiment performed on a coupled Oscillating Heat Pipe and PCM Model resulted that the effect of installation angle of the Closed Loop OHP has minimal effect when the angle is less than 30 degree, during the discharge process. [26] proposed a PCM and oscillating heat pipe based BTMS for dissipation of heat from a rectangular battery surrogate of 115 mm height and 90 mm width where they found that when the terminals of the battery surrogate are at distant from the adiabatic section of the OHP, battery temperature is maintained uniformly over the module. Table 4 shows the Summary Heat pipe and heat pipe assisted studies.

### Table 4. Summary Heat pipe and heat pipe assisted studies

| Author | Cooling Technique | Condenser cooling technique | Battery load | T<sub>amb</sub> | Maximum cell temperature |
|--------|-------------------|-----------------------------|--------------|--------------|----------------------------|
|        |                   | With Free convection         | With pure PCM | %reduction compared to Free convection |
| [3]    | Flat plate loop   | Water, acetone 400W and alcohol | 25 - | 50 - |
|        | Heat pipe         |                             |              |              |
| [4]    | Flat Heat Pipe    | Air cooled | 3C | 20 | 48.8 | 21.5 | 55.94 |
| [5]    | Round Heat Pipe   | Air cooled | 54W | 20 | 58 | 28 | 51.72 |
| [6]    | FERC Heat pipe    | Water cooled | 50W | 25 - | 48 - |
| [7]    | OHP+PCM           | Water cooled | 80W | 23 | 80 | 60 | 33.33 |
| [8]    | Flat Heat Pipe    | Water cooled | 3C | 25 - | 27.62 - |
| [9]    | HP+PCM            | Water cooled | 400W | 25 | 88.2 | 53.4 | 65.16 |
| [10]   | Flat Heat Pipe    | Air cooled | 1.5C | 26 | 64.8 | 37.1 - |

[27] investigated a combined PCM (Rubitherm GmbH, RT 50), heat pipe and fins-based model of BTMS for heat dissipation from a A4 sized laminated type Li ion battery pack prototype of 194mm length and 144 mm width. They reported that the temperature of the mimic battery does not surpass thermal runaway temperature which infers that the system is safe for use and promising. [28] developed a computational method to predict thermal characteristics of the battery. Maximum temperature of 37.5 °C is reported with BTMS based on Heat pipes. A comparison was shown with forced and natural air cooling.

4. Conclusion and future work
An effective BTMS system is essential for optimal performance, longevity, and safety of the Lithium-ion battery cells. Many experimental investigations were reported the thermal behavior of battery cells using a battery prototype in a controlled environment or a real lithium-ion battery pack under different loadings. Simulation and computational approaches were also attempted using FEM solvers and CFD software COMSOL and FLUENT. This paper extensively studied the Passive cooling techniques for BTMS using PCM, heat pipe and both PCM and heat pipe coupled. From the study, it can be inferred that although a lot of studies were done on the passive cooling approach of the thermal management system, the search for an effective BTMS is still going on. It can be concluded that, PCM with optimum number of longitudinal fins are suitable for passive cooling method applications using extended surfaces. It is found that PCM is an effective way out but accounting for its leakage it must be embedded in a graphite matrix or metal foam for better conductance. The passive cooling techniques may not be sufficient in high load applications and there a combination of PCM and liquid cooling could be an effective solution. The most preferred PCM is paraffin wax but because of its low thermal conductivity, one or more thermal property enhancement method is used along with it. Metal foams, carbon nano particles, metal additives, EG composites, graphene coatings, micro encapsulations, internal and external fins are few popular methods of thermal conductivity enhancement methods. Metal foams with low porosity and pore density is desirable. Usage of heat pipe for thermal management has also gained popularity among the researchers in EV application. Majority of the research focused on structure, working fluid and cooling method of condenser in heat pipe technologies. Combination of PCM, heat pipe and extended surfaces also found suitable in heavy loading applications and the effectiveness of combined heat pipe and PCM assembly is more as compared to the BTMS using heat pipe alone.

Future work may include a BTMS using heat pipe and PCM assembly where a PCM and heat pipe assembly having the optimal heat dissipation rate could be coupled considering the cost, space, weight and heat extraction capacity. Moreover, in the future, thermal load of the battery may rise due to demand for batteries having high energy density, so an appropriate BTMS to tackle all these issues along with issues like thermal runaway is much sought for.

Acknowledgements
This research work is supported by the Collaborative Research Scheme (Project ID 1-5728014705) of National Project Implementation Unit, TEQIP III, MHRD, India.

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