REVIEW ON BATTERY THERMAL MANAGEMENT SYSTEM USING PHASE CHANGE MATERIAL

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ABSTRACT

Batteries are used in automobiles, and other areas where power is required. Many batteries were used in commercial applications like the electric vehicles. When more heat is generated, the temperature of the cells in the battery packs also increases. This increase in heat generation rate leads to firing issues. Thus a suitable cooling method should be enabled to reduce the heat generation. Phase change materials have an supporting and promising properties in the reduction of achieving the extreme temperature under higher accelerating conditions, which leads to damage in the battery cells. The desired temperature range in the batteries can be maintained by the application of PCM. By enabling PCM in the battery thermal management system, the temperature rise can be reduced to half in the battery packs. The maintenance of the PCM is also easy.

Keywords: Phase Change Material, Battery Thermal Management System, Lithium ion battery, Temperature reduction, Electric Vehicle.

I. INTRODUCTION

The world has been facing severe pollution issue in the field of automobile engineering due to the release of hot gases into the atmosphere. The hot gases are released as a process of combustion. The exit of several other gases from many other process involving the release of heat increase the warmness of earth. Bikes, cars, heavy load trucks and other vehicle running with petrol or diesel as the main source of fuel, releases more exhaust gases into the atmosphere. The main emission are hydrocarbon, carbon monoxide, nitrogen di oxide. These gases reaches the surface of earth and damages the ozone layer. Thus an alternate solution is needed to reduce these effects. To provide a sustainable and pollution free environment, electric vehicles have been developed. The main source of power to the vehicles is provided by the battery. The batteries provide electrical energy to drive the vehicle.

II. LITHIUM-ION CELL

The lithium ion cell is an electrochemical energy storage device in which the electrical energy is provided by using chemical reactions. Commercially lithium ion cell is employed in electric vehicles due to its higher energy density, higher power higher performance and longer life. The operating temperature of the cell varies from 20°C - 60°C. Beyond this range, the temperature of the cell can be maximum and it may leads to firing issue. The battery operated with a medium temperature range 25°C - 40°C will retain a maximum life cycle. The lithium ion cells are available in forms of coin cells, cylindrical Li–ion cells and in rectangular pack. The most preferable form is the cylindrical shape which have the desired characteristics as said above.

2.1 Components Of An Cylindrical Li-Ion Cell

A cylindrical li-ion cell construction is as follows:
2.2 Heat generation in the battery

The generation of heat in the battery pack depends upon the charging and discharging cycle. More heat is generated during the discharge cycle. When the discharge rate increases, heat generation also increases. Experiments were conducted to measure the temperature of the cell in the anode portion, in the cathode portion, and in the middle portion to identify where large amounts of heat occur. The heat generation is mainly dependent on the C rate. C rate is the charge delivery rate of the battery. It is also defined as the ratio of discharge current drawn to the theoretical current drawn in which the battery can deliver its nominal rated capacity in one hour.

III. TYPES OF COOLING SYSTEM

The cooling system employed for thermal management in the batteries is performed in two ways:

a. Active cooling methods

b. Passive cooling methods

Active cooling methods: This method employs air or liquid as the cooling system employed to the batteries operated at higher discharge with maximum temperature to minimize its temperature increase. The coolant used are water, glycol, acetone, etc.

Passive cooling methods: The PCM cooling technique is preferred over the active cooling system due to its excellent temperature reduction and maintains the temperature of the battery pack within possible safety ranges and it also requires less volume. The coolant used are sodium polyacrylate hydrogel, hydrofluoro ether, etc.

IV. DESIGN PARAMETERS FOR THE BATTERY WITH PCM

To develop a design for the battery module with PCM, the parameters to be selected as follows:

a. The number of cells needed to conduct the experiment

b. The shape of the cell
c. The power capacity of the cell
d. Analysing the pcm to meet the phase change requirements.
e. The quantity of pcm needed to design the pcm module for the battery pack.
f. Pcm thickness for its heat conduction and distribution.
g. Selection of the operating temperature range of the battery.
h. The heat flux in the battery pack.
i. The duration of charge and discharge of the battery pack.

V. BATTERY THERMAL MANAGEMENT SYSTEM

List of Notation:

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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>PCM</td>
<td>Phase Change Material</td>
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<td>CPCM</td>
<td>Composite Phase Change Material</td>
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<td>TMS</td>
<td>Thermal Management System</td>
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<td>ITMS</td>
<td>Integrated Thermal Management System</td>
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<td>EV</td>
<td>Electric Vehicle</td>
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<td>C rate</td>
<td>Charge or Discharge Rate</td>
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<td>C</td>
<td>Celsius</td>
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<tr>
<td>T_amb</td>
<td>Ambient Temperature</td>
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<td>T_max</td>
<td>Maximum Temperature</td>
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<td>BTMS</td>
<td>Battery Thermal Management System</td>
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<td>3D</td>
<td>Three Dimension</td>
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<td>Li-ion</td>
<td>Lithium ion</td>
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<td>Al_2O_3</td>
<td>Aluminium Oxide</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>EG</td>
<td>Expanded Graphite</td>
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<td>AC</td>
<td>Air cooled</td>
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<td>EEV</td>
<td>Electronic Exhaust Valve</td>
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<td>HP</td>
<td>Heat Pipe</td>
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<td>PCMP</td>
<td>Phase Change Material Plate</td>
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<td>DCM-PCMP</td>
<td>Double Copper Mesh Phase Change Material Plate</td>
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<td>SiC</td>
<td>Silicon Carbide</td>
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<td>ΔT</td>
<td>Temperature Difference</td>
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<td>TEG</td>
<td>Thermo Electric Generators</td>
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5.1 Air Cooling

The heat generated in the battery can be removed through forced air convection. By employing air cooling, it makes the additional compounds into the system and makes the system bulk and complex. Though air cooling removes most of the heat, it cannot control the heat dissipation at high discharge rates.

Yuqian Fan et al carried an experimental study to test the effects of cell arrangement, air inlet velocity, air inlet temperature and discharge rate in li-ion. Battery pack cooled by a fan with all these effects, the efficiency of air
cooling system was analysed. The battery is discharged at 2C with $T_{\text{amb}}$ of 20°C for the three different configurations of battery pack. The aligned configuration of the battery pack has the best cooling effectiveness and temperature uniformity and also occupied less volume, followed by the staggered and cross arrangement. Increasing the air velocity decreases the temperature rise and improves cooling performance and also the energy efficiency factor also decreases. The increase in air velocity leads to decreasing the evaluation parameters with a negative exponential form. The minimum temperature always occurs from the inlet to the outlet. As the discharge rate increases, the maximum temperature rise also increases. By increasing the air inlet velocity, the curve for the temperature rise moves downward. This describes that the effectiveness of air cooling is gradually enhanced. The power consumption increases exponentially with the velocity of inlet air and the dissipation of heat also rises. The aligned arrangement has the less energy consumption and is 23% less than the cross arrangement. Increasing the discharge rate greater than 2C will not remove any additional heat by the forced air cooling system and results in thermal runaway[1]. Jibing Jiang et al analysed the thermal convection in a li ion battery using lattice Boltzmann model. The system has been developed to prevent the thermal runaway and the results shows the reduction in thermal runaway in batteries during forced convective heat transfer. The numerical lattice Boltzmann model is validated by the square enclosure with a heated circular cylinder through natural conduction. To manage the thermal convection issues and to solve, the study has been conducted and concluded that increasing the heat transfer co-efficient may have better cooling performance[2].

5.1.1 CPCM with Air Cooling

Yongqi Xie et al investigated cpcm coupled with an air cooling system and compared with the air cooling system. n-eicosane paraffin with copper foam is employed. The factors like airflow rate, pcm liquid fraction and ambient temperature were considered. The cooling system of air cooling system coupled with pcm is better than the air cooling system. Increasing the air flowrate decreased the battery temperature and maintain the battery temperature stable. At fixed $T_{\text{amb}}$ and air flow rate, the liquid fraction of pcm would not show significant variation in phase change temperature and there is no sharp rise in temperature even the pcm is fully melted. PCSEUs hold the solid state pcm and most of the heat is dissipated in the battery by the cooling air. A small amount of heat is stored in the pcm as sensible heat. There will not occur any change in the thermal resistance between the battery cell and the pcm. The air cooling has a positive advantage in removing most of the heat generate in the battery. By varying the $T_{\text{amb}}$ the heat dissipation of air cooling is varied and the heat absorption of pcm is not changed. The ITMS with two operation modes a) with pcm as the only heat sink in the discharge process, no battery power is consumed as there exists an external power to drive the cooling fan. b) working of ITMS with the charge and discharge cycle has the airflow rate smaller an the battery pack is not cooled completely and the initial temperature of the next stage has been higher. It is suggested to keep airflow rate 300 m$^3$/h. increasing the airflow rate results in poor temperature uniformity and also increases pressure difference. The pressure difference increases the power of the cooling fan and battery power is greatly consumed. The air cooling will reduce the battery energy efficiency[3].

5.2 Liquid Cooling

Ke Li et al proposed water cooling techniques to cool the li ion battery pack by both numerical and the experimental simulation. Though the water cooling technique improves the thermal performance of the battery pack an additional systems like phase change materials that are needed to construct a real battery pack for operating at wider cycling rates. The thermo-physical and kinetics parameters shows an enlarged deviation in the temperature distribution in the battery pack. The water cooling technique is suitable for the dynamic cycling of the battery pack with low cycling rate[4]. Yoong Chung et al made a comparative study on the different structural designs employed in the battery thermal management systems. A thermal model with liquid cooling system is developed with the li ion pouch cell with the cell surrounding the insulation case, metal fin and thermal pad placed on the cooling plate. The cells are arranged in stacks. This model is compared with the typical fin cooling structure of the battery pack. The purpose of the study is to improve the temperature uniformity and cooling performance by comparing various pack level designs with different disposition of battery pack and cooling plate. The poor thermal conductance designs made with metal fin and cooling plate is contributed by the thermal resistance between the stack bottom to the cooling plate of the battery pack. By comparing the various structural designs of the battery pack, the large scale battery packs for electric vehicles can be designed and the expectancy of thermal management in cooling performance can be achieved[5]. Limin Song et al proposed a novel conjugate cooling configurations using pcm and liquid cooling techniques and investigated the
thermal performance of the module. Three dimensional numerical models are also proposed to represent the cooling of battery and battery module which contains mini channel cold plate through heat spreading plate and thermal column structures. De-ionized water is used as the coolant. The paraffin used is paraffin. The distance from center to center of the adjacent channel under the battery is taken as 4mm. The battery is kept at a nearly isothermal state during the large flow rate in which the liquid coolant works as a thermal shunt. In the thermal management system, the conjugated cooling is more effective than single liquid cooling particularly in pcm melting process. The steady state temperature of the battery is lowered due to the presence of pcm compared to the liquid cooling without pcm. The melting fraction of pcm can be improved by optimizing the structure of the conjugated cooling configuration[6]. Suman Basu et al designed an coupled 3D electrochemical thermal model for battery pack which aims to reduce the leakage problems and to increase the heat transfer efficiency by the way of liquid cooling technique with highly conductive aluminium metals for heat conduction and transfer and it also acts as a separator between cell and coolant. The cells are wrapped by aluminium to remove heat through thermal conduction. The heat from the cylindrical cells is transferred to the coolant channel and finally reaches the coolant liquid. The test is performed with connecting the cells in series and then in parallel. This technique can also reduce the number of sensors and control system complexity. The conduction elements also makes the temperature uniformity in the battery pack. This system can work efficiently even at low coolant flow rates at higher discharge rates[7].

5.2.1 Minichannel Cooling Systems

Chuanjin Lan et al designed the aluminium minichannel cooling system with different designs of tube systems to study the temperature distribution at different discharge rates of the battery. The cooling fluid used is the liquid water. Numerical modelling of the battery is designed and the COMSOL finite element software is used. In the model validation free tetrahedral mesh construction is preferred to use. By validating the fine and coarse mesh the maximum temperature and velocity difference is 1% and the pressure difference is 3%. The coarse mesh design is used since the maximum temperature obtained in coarse mesh is 34.57 °C which is slightly lower than the fine mesh of 34.87°C. The validation of mesh design is not enough for the study and the numerical results of heat transfer and laminar flow are also need to be validated. The comparison made between the energy conservation and the pressure drop makes the validity of the numerical study. The pumping power assumed to be about 5 milliwatt. The thermal management results are obtained with varying discharge rate and the flow direction to increase its performance. The flow is in the laminar region. The maximum temperature where observed in the middle of the battery. When the flow rate increases, the maximum temperature and difference in temperature decreases. For the high discharge rate, increasing minichannel flow rate is not an suitable solution but reducing the cross plane thickness will be an suitable thermal management system. The best results are obtained by alignining the inlet on one side of the battery rather than alternating setup of inlet and outlets. By using the minichannel cooling system the maximum temperature rise and the difference in temperature is greatly reduced in the battery[8]. Zhongao Rao et al developed a simulation based on pcm/minichannel coupled BTMS and a3D battery thermal model to get a suitable design for btms. Pcm is filled in the gaps between the rectangular batteries. Water has been selected as the cooling medium. The properties of pcm is assumed to be constant in both the solid and liquid phases while the radiation heat transfer and thermal contact resistance have been neglected and also the volume change of pcm and motion of solid pcm is also been neglected. The battery was in adiabatic condition and the part of the heat generated can be taken away by the cooling water and also natural convection has been considered it also takes the generated heat by air. During the melting process of pcm, there will not occurs the natural convection within the pcm since, effect of gravity is neglected. The number of channels cannot be less tan four inorder to maintain the temperature of the whole system. Eight channels were considered inorder to control the T\text{max} and ΔT. The liquid fraction of PCM tends to decreased by increasing the mass flow rate and with increase in phase change temperature. The thermal conductivity with 0.6 W/mK is suggested to improve the thermal performance of the system. Increasing minichannel may decrease the T\text{max} and increase the ΔT which will damage the battery. Pcm/minichannel coupled cooling system have better performance than the other cooling system[9].

Zhen Qian et al introduced a minichannel cold plate coupled with liquid cooling system to maintain the temperature of the li-ion battery pack and to provide assistance in the design criteria for EV. The variables like mass flow rate, direction of flow, number of channel required, channel width in minichannel cold plate has an effects on the thermal performance of the battery pack. Two design systems with y direction rake have two channel numbers and z direction rake with different channel numbers with symmetric designs are examined. The energy consumption may be minimized
by using a wider channel, which minimize the pressure drop in the system. The channel numbers were increase to 7 from 2. Increasing more channel makes more cost. However decreasing the number of channels result in increasing pressure drop and cooling performance is also worse. 5 channel cold plate is enough to make cooling performance in this study. The temperature gradients in the liquid flow direction can be reduced by increasing the inlet mass flow rate. The temperature in the near electrode area is always higher than the other surrounding area due to the fact the temperature is uniform in all area except the near electrode area. The battery are sandwiched with the two cooling plates in the z direction rake design systems. And the design system with 4 channel cold plates cannot meet the requirements of the whole battery pack due to higher temperature in the first cell. So additional cooling plate is needed and 5 cold plate is made enough increasing than that will not give any additional cooling performance[10].

Huaqiang Liu et al investigate the effects of nanofluids in the minichannel based thermal management system in the high power prismatic li-on battery. The study aims to find the properties and effectiveness of nanofluids in bms in accordance with the base fluids, volume fraction, flow velocities and inlet temperatures. The base fluids and their corresponding nanofluids are compared. The base fluids like water, ethylene glycol and engine oil. Al₂O₃ is used as the nanoparticle to be suspended in the base fluids. The heat transfer coefficient between the battery cell and fluid channel increases with the water/Al₂O₃ fluids. Among these fluids, water gives the best cooling effect. When 5% Al₂O₃ is suspended in base fluids, the thermal conductivity is further increased. The thermal performance of all base fluids with the nanoparticle is improved under different discharge rate with the increase in fluid pressure drop. To improve the better cooling in the battery cooling system, it is suggested to precool the coolant which will results in increasing the energy consumption and lowers the cell highest temperature. Nanoparticle addition shows a reduction in temperature rise and temperature difference also shows slight variation[11]. Yuqi Huang et al introduced the streamline concept to design a mini channel cooling plate and to optimize the heat exchanger performance in an inner field. Grid 5 is induced in the system to reduce the temperature and pressure differences and the corresponding mesh generating rules are implied. Six 3D models were established and discretized for validation. The pressure drop suggested by RAO et al well fit the system and the error was less than 4.5% which proves the designed system is acceptable and reliable. The pressure drop in even number cold plate is higher than the odd number cold plate. Multi channel structure has been employed in the cooling plate. Five different channel plates are compared with the conventional shape channel and the streamline shape channel to determine its performance. In the stream line flow channel, vortex and turbulence flow can be avoided to improve the cooling performance. The velocity of stream line channel model with odd number channels are lower than the straight channel models, whereas in straight channel models the velocity difference of the odd channel numbers between the middle channel and the other channel is quite high. Increasing the mass flow rate decreases the temperature uniformity. Operating the mass flow rate at 0.001 and 0.002 kg/s states, temperature uniformity in straight channels with odd numbers have better performance and the temperature uniformity in streamlines models are significantly improved when the channel numbers are even. When the number of channel is increased, streamline model shows good uniformity[12].

5.2.2 Refrigerant Coolant System

Seonggi Park et al developed a numerical model based on active thermal management system using refrigerant as an coolant. A LiFePO₄ cell is used in this study. The study compared the numerical models of the pcm based passive TMS with the refrigerant cooled passive TMS. Two different types of pcm are used in the passive tms in which the heat is transferred by natural convection from the battery module to the pcm and escapes into the atmosphere. In the active cooling TMS, mini or micro channel heat sinks are used, which performs two phase heat transfer of refrigerants, i.e. liquid vapor two phase cooling. The cooling performance is carried out under various single discharge and cyclic operating conditions. The governing equation of the battery cell and pcm based passive tms and refrigerant cooled active tms are solved in the MATLAB software using finite difference method. The cell thermal conductivity was divide into in-plane and through-plane thermal conductivity. The performance revealed that, by decreasing the discharge rate at a given refrigerant temperature, there is a decrease in both the maximum temperature and temperature difference. As the mass flow rate increased, the maximum temperature in the module decreased and the latent heat capacity may be decreased. Under mild operating conditions, the active and passive TMS are excellent in performance whereas in stressful operating conditions (high discharge rate and ambient temperature) the maximum temperature and temperature non-uniformity in the module are increased than mild operating condition. In cyclic operating condition, the pcm based tms is not able to recover the latent heat capacity of the pcm than the refrigerant cooled active TMS. The
refrigerant cooled active TMS have excellent performance with the two-phase cooling which recovers the latent heat capacity of the refrigerant[13]

Jiwen Cen et al introduced the air cooling refrigerant to cool the li ion battery pack. The liquids used in the Air Cooling BTM is water and glycol solution. The refrigerant flows through the battery pack directly to reduce the temperature rise and this system eliminates the use of heat exchanger between the refrigerant and coolant. The battery module is designed as the finned tube heat exchanger system in which The aluminium frame has pentagon shape in the outer and the inner surface has round hole to hold the battery and finned tubes are also presented in the module. Thermal silicone is applied in the contact surfaces for improving heat transfer. Two types of refrigerant circuits are investigated, one with the inlet and outlet at same end of the module and the other with inlet and outlet located on opposite end of the module. Two electronic expansion valves are used to one controls the refrigerant flow into the cabin evaporator and another one controls the flow of refrigerant into the module. When the mean temperature in the battery module is higher than the preset temperature, EEV 1 opens to cool the battery pack, when the mean temperature is lower EEV1 closes. The EEV 2 is always opened. During the opening of EEV1, the power consumption of compressor is suddenly increased. Necessary power rate should be employed for cooling the battery pack. Change in quality and the pressure drop in flow path brings the refrigerant to the superheated state which increases the temperature of the refrigerant[14].

5.2.3 Serpentine Channel Liquid Cooling Plate Exchanger

Lei Sheng et al developed a numerical model in the thermal management of li-ion batteries using serpentine channel liquid cooling plate exchanger to develop an optimal design of the battery thermal management system. The serpentine LCP has designed with two inlets and outlets and the system has an advantage to arrange the inlet and outlet on the opposite side than on the same side. And the numerical study is based on the liquid flow direction, liquid flow rate, LCP channel width and the operating current. The use of the cooling plate is to control the undesirable temperature distribution in the battery pack at higher operating current. In the channel design it is suggested to have lower temperature rise and lower temperature standard deviation of cells for better tms. By increasing the flow rate, the ratio of power consumption of the LCP increases. The ratio of power consumption decrease with the increase of channel width. The LCP channel width of 12 mm is considered to be best for the temperature control. The dimensionless analysis is carried out for the hydraulic performance of LCP[15].

5.3 PCM Battery Cooling System

The active cooling system using liquid coolant have higher heat capacity, thus it proves to be more efficient than the air cooling system. Employing heat pipes may have higher heat conductivity and reduce the maximum temperature under stressful conditions. The thermal management can be achieved by using pcm, further to increase the thermal conductivity metallic foams can be added to the pcm or by using metallic foams with fins[16].Huan Yang et al presented an correlation between the melting process of pcm (paraffin wax) and the heat transfer characteristics of it in a cylindrical battery. In the visualization experiments a comparision has been made between aluminium metal housing and acrylic housing with the use of pcm for its thermal characteristics. The battery not only transfer the heat to the pcm and also heat itself and its components. Both the housing show similar thermal characteristics but differ in its melting process because the pcm melts in the early stage and increases the temperature of the battery due to the weak heat conduction in the acrylic housing than the metal housing. This results suggests that specially designed metal housing can increase the heat transfer characteristics and acrylic housing is inefficient for heat transfer[17].Tianshi Zhang et al conducted an experimental research by employing phase change material in the thermal energy storage units to characterizes its thermal effects. By enabling pcm in the thermal energy storage units, the system waste heat should be utilised and reused. The research work is carried out with a thermal energy storage unit with three pcm’s of different melting point to extend the range of applicable temperature and to fulfill the different heat sources required for different classes of storage units. This multiple pcm combinations helps in the waste heat recycling. The pcm thermal energy storage unit consists of flat tubes and corrugated fins. The main purpose of constructing this system is to study the heat storage and release characteristics of the pcm heat storage unit. In between the flat tubes pcm is filled. The analysis of heat storage and heat release is determined with the liquid flow rate, initial pcm temperature, inlet liquid flow temperature and the melting point of the pcm. The thermal energy storage unit performance was calculated in the basic condition. The latent heat has an effect of its inlet temperature in which the latent heat exceeded
the sensible heat in the pcm. In case of melting point of pcm, higher the melting point of pcm, higher is the liquid outlet temperature. By varying the liquid flow rate, the heat transfer enhancement could not be realized. The cascading combination of pcm has two orders of ascending and descending melting point in which there is a variation in the outlet liquid temperature. The thermal efficiency of heat storage units during descending order of heat storage and ascending order of heat release is calculated. The calculated heat storage efficiency is much lesser than the real vehicle heat storage system. The heat storage and release rate increases with the increased liquid flow rate. This cascading pcm combination may be helpful to recover the waste heat in the electric vehicles [18].

Hamid Jannesari et al introduced potassium poly acrylate, an superabsorbent gel win the thermal management of cylindrical LiFePO4 batteries. 5% weight of polyacrylate with water is preferred to produce hydrogel due to the high specific heat of water, other than that hydrogel will not be formed. The experiment is conducted and compared by filling the gel over the empty spaces inside the battery pack and filling the gel to empty spaces between the cells. To reduce the maximum temperature in the battery pack, all the empty space should be filled with hydrogel in the entire pack and there is significant temperature difference observed with the use of hydrogel and not applying hydrogel. The hydrogel can decrease the battery pack temperature without increasing the pack volume [19].

Ashima Verma et al made a comparative study on the phase change material. Fin structure assisted pcm has been investigated. The pcm used is capric acid, which is fabricated at different thickness are attached to the periphery of the battery pack. The design and dimensions are taken from the study made by Jawani et al. The heat generation rate depends on the discharge rate as well as the ambient temperature. Capric acid is suitable to absorb excess heat than paraffin wax. When the electric vehicle is accelerating at lower speeds, the temperature of the battery module will be maintained at a stable range. If the electric vehicle is operating at higher speeds, the temperature of the battery module will gets increased and it will disrupts the operating performance. The PCM with less thickness is proved to be optimum and lowered the maximum temperature. Ansys 19 design modeler, is used to design battery pack with and without pcm. Ansys fluent is used to check the temperature distribution and thermal characteristics of the battery pack at higher discharge rates. Tetragonal mesh is applied over all geometry using ANSYS 19 mesh. The temperature difference at higher discharge rate with and without PCM with respect to time has been compared with study made by Jawani et Al [20].

Jiajia Yan et al declares that at the higher the extraction of current from the batteries, the cooling system of pcm is superior than that of natural convection system in the fact that latent heat of pcm is not utilized at low current rate as the pcm did not reach the phase change temperature. The pcm used is a composite of paraffin and expanded graphite. Three types of paraffin wax with different melting temperatures 36°C, 45°C, 58°C are used to optimize the phase change temperature. The pcm with 36°C has one phase change peak while the other two pcms have two phase change peak. The enthalpy of the pcm with 36°C has the least enthalpy due to the larger mass fractions of hydrocarbons with low melting point. To determine the thermal characteristics, a single battery was tested under two modes of dynamic cycling of battery with the constant-current charge process and the dynamic cycling of battery with constant–voltage charge process. The temperature and temperature difference increase with increasing the cycle rate in both process. The variation shows that near the positive electrode the temperature is higher due to larger current density than the middle of the battery in the Constant Current process and generation of heat is smaller in the Constant Voltage process due to the smaller current density and reduces the temperature of the whole charging process. The natural convection has two temperature peak in one cycle while the pcm plays a buffering role and has only one temperature peak under the temperature curve. Proper increasing of laying aside time is to be considered for beneficial activities of the pcm. The maximum safety limit is exceeded by the natural convection system and results in thermal run away and the pcm system controls the maximum temperature rise at higher current rate by utilizing the latent heat. The pcm with the phase change temperature of 45°C is recommended to utilize in the real battery back system because the temperature range is neither too high nor too low while the pcm with 36°C exceeds the acceptable safety limit and the pcm with 58°C has the highest temperature range and it did not reach the phase change temperature [21]. T. Zhao et al derived an enthalphy based discrete thermal modeling framework using the granular phase change materials. The encapsulated pcms have the large heat transfer area and reduce the reaction of the pcm with other materials are which are outside the environment. The model is considered with the heat conduction and phase transition process of the pcm and it is validated by an Stefan problem which describes the temperature distribution in a homogenous medium during phase
change process. The charging or discharging time of the battery can be reduced by using smaller pcm capsules or with increasing the packing densities[22].

Benli Peng et al suggests that effective thermal storage systems can be obtained by using high thermal conductivity and temperature-independent density pcm during charging and discharging process. A eutectic pcm and paraffin wax, with high thermal conductivity ratio and similar volumetric energy density is used. Using a two dimensional enthalpy-porosity method, a numerical melting/solidification model was established. A cycling experiment was carried out to confirm the formation of gap in the solid paraffin wax. Natural convection may suppressed by top heating. The whole charging process of eutectic pcm is dominated by the conductive heat transfer. The intense and strong natural convection significantly enhances the charging rate and also shortens the paraffin wax’s total charging time. The charging performance of paraffin wax is affected by heating orientation. The charging process can be enhanced by the natural convection. The charge efficiency can be calculated by the ration of average charging efficiency to the heating power. Thus high thermal conductivity pcm can achieve more stable temperature evolution in charging process and also maintains stable temperature during discharge process. Highly conductive pcm with temperature-independent density insensitive to orientations while pcm with low thermal conductive with obvious temperature dependent density suffer from orientations[23].

Songmengjie et al used three types of organic pcm’s like palmitic acid, lauric acid, myristic acid which are used in the buildings and the industrial waste heat recovery, to establish the thermal stability of the materials. The tailor-made experimental setup is introduced and the experiment is conducted with three different composites by mixing capric acid with three different pcm’s of mass ratios of 1:9 for capric acid & lauric acid, 4:6 for capric acid & myristic acid, 11:9 for capric acid & palmitic acid. The system is carried out with thermal cycling number upto 4000. The composite with capric acid and myristic acid shows the best thermal performance because its phase change temperature has not changed and the heat of diffusion decreased to 4.5% after 2000 thermal cycles[24]. N. Javani et al conducted an numerical simulation of the li ion battery provided with pcm layers of different thickness of 3mm,6mm,9mm,12mm and observed the temperature uniformity and reduction. Finite volume method numerical simulations has been carried out. Enthalpy-porosity technique is applied to simplify the methodology. The terminals of the battery acts as a fin for cooling and there will not any heat generation because the spacing between the cell margin and pcm is very thin layer of metal thus decrease the heat transfer between the cell and terminals. The battery with pcm of thickness 3mm provides temperature uniformity by 10%. And the pcm with 12mm thickness reduced the maximum temperature rises upto 3.04K. A larger pcm thickness can provide better cooling in the cell. The amount of pcm will extend the time interval by absorbing heat from battery to pcm. If once the thermal conductivity is not constant in all the directions, then the heat difference rate will not be equal in all surfaces[25].

5.3.1 Composite Phase Change Material

The composite pcm has been developed in order to overcome the low thermal conductivity of pcm. The leakage properties of paraffin has been reduced by the addition of metal composites and enhanced the heat transfer characteristics. Xuan Zhang et al developed a composite phase change material using kaolin/expanded graphite/paraffin. The main reason for developing this pcm is to reduce the leakage properties of paraffin and volume change in the process of melting which may results in short circuit and improves security risks. To overcome these effects adsorption additives are needed to be used. Another promising factor is its performance in improving the thermal management system. The battery thermal management system has an significant attention on pcm due to its low cost, excellent thermal performance and its easy maintenance. The thermal performance of kaolin and expanded graphite were compared based on its toxicity, cost, performance and stability. Previous work by Lv et al prepared the kaolin/paraffin composite which gives a satisfactory stability but the only outcome is the large fraction of kaolin in the composite restrained the heat capacity. To provide a larger latent heat in the adsorbent effect of paraffin, expanded graphite has been selected as an other adsorbent materials to enhance the kaolin. The mixture of these ternary composites were tested for its stability and leakage effects. The lesser the paraffin leaks on the filter paper greater is the stability. A single 1965140 rectangular battery and a battery pack were used to measure the temperature controlling performance. The temperature rise of the single battery and a battery pack were measured at different discharge rates. The discharge process was carried out in a constant temperature and humidity chamber. The temperature rise and temperature difference of the single battery and battery pack with and without pcm were measured. In the battery pack each side of every battery is covered with a air...
or composite boards. During this process a solid-solid phase transition occurs before the melting of pcm. The latent heat is very small and the TMS of batteries depends only on solid – liquid phase change latent heat. The composite boards successfully controlled the maximum temperature in the battery pack at higher discharge rates. By using these ternary composite mixtures the leakage properties have been reduced and controlled the maximum temperature in the single battery and battery pack. The addition of composite improves the temperature distribution uniform even at higher discharge rates[26].

Yanqi Zhao et al developed a composite phase change material to increase the thermal conductivity of the pcm. The pure pcm is not sufficient to transfer the heat generated in the battery cells. Pure pcm has low thermal conductivity, which affects the temperature distribution. In this, copper foam is used to enhance the thermal conductivity of the pcm. The active liquid cooling method is combined with the passive pcm cooling techniques. The system and the battery is in direct contact which provide temperature uniformity. The heat generated in the battery during discharge cycle is used as the input source for the simulation. The battery was first charged by galvanostatic mode. 20 lithium ion cells were used and a copper pipe was used for the fluid flow for cooling. The cooling system was examined with two types of material, one with the copper foam filled with paraffin and the other is with commercial pcm from rubitherm. The thermal characteristics of the single battery was observed with the different charge and discharge rate, time taken for charging and discharge and corresponding heat generation owing to increase the temperature rise in the module. It is concluded that the heat generation rate of lithium ion cells increases with the increase in discharge rate. The temperature of the battery module was decreased 14° C than the pure pcm. Thus The copper foam can maintain the temperature of the battery surface as required. Along with the pcm, liquid cooling also contributes to a better temperature reduction in the battery[27].

Abid Hussain et al designed and experimentally verified a novel composite made of nickel foam and paraffin wax. Four nickel foam samples with different porosities and pore densities are used. Holes are created in the foam to hold the batteries which reduces the volume of the battery pack and reduces total weight in case of large scale utilization. The batteries are tested with three modes to compare the temperature reduction. The modes are natural air convection, with pure pcm –paraffin and with the nickel foam-paraffin composite. The temperature rise and decreases are noted during the charging and discharging phase. The generated heat is distributed efficiently throughout the nickel foam – paraffin and also the paraffin has been filled uniformly in the pores of the metal foam. The temperature difference observed is minimum in nickel foam – paraffin than the natural air convection and the pure pcm. Heat convection is an important mode in reducing the temperature. The decrease in temperatures has positive effect in increasing the thermal conductivity of the paraffin and also increases the heat transfer from the battery surface. The experiments are repeated and it reveals that there is no significant reduction in the heat storage capacity[28]. Zhongao Rao et al experimentally studied the temperature reduction and distribution in the electric vehicle battery pack using paraffin/copper foam. Copper foam is added to paraffin to increase the thermal conductivity of paraffin. The single battery cell represents that increasing the discharge rate, the discharge time increases, the discharge stability decreases and the heat generation is also higher with increase in charge and discharge current. The temperature in the positive electrode is higher than the negative electrode and middle wall. In the whole discharging process the local temperature difference is also changed. After the battery module have been inserted in EV, the vehicle speed varies with the road condition and the temperature of different battery cells and the local temperature difference has fluctuations. At 3.5C discharge rate and increasing the time, temperature exceeds 50°C and the temperature in the centre of the module could not be transported faster and local temperature difference increased. When the battery module with paraffin/copper foam is tested under different ambient temperatures at 5°C rate. when the ambient temperature is increased the maximum temperature of the battery module also increased when T sub is 29°C and 33°C the T max in the battery module is 40.89°C and 42.33°C, and the local temperature difference was 3.24°C and 4.08°C. With the high thermal conductivity of copper foam, the accumulated heat in the contact surface of paraffin and battery cells is transported outside and transported faster into paraffin to maintain the operating temperature and limits exceeding the maximum temperature[29].

Weixiong Wu et al developed a 3D model of prismatic battery for optimizing the thermal management system by without considering the electrochemical part of the cell and the results are validated by using experimental data. for the different shape stabilized pcm configurations, the temperature field and the heat transfer characteristics in the battery is discussed. The surface heat transfer coefficient on temperature rise and distribution of temperature during discharge process and the effects of thickness of pcm is illustrated. Pcm/expanded graphite is used to form a plate shape structure.
The cell is divided into positive and negative terminal and the core as three parts. This composite provides improved thermal conductivity and shape stability as there will not occur any leakage during solid liquid phase transition. The pcm plate is located at broad side surface, narrow side surface, and wrapped around the cell. Volume of pcm is same but the thickness of pcm is varied in the pcm plate. The battery structure is symmetric in the z direction, so half plate is considered to reduce computation load. In developing the mathematical model and numerical study, Enthalpy method is adopted. In this, thermal equilibrium exists between the pcm and EG. No liquid flow occurs in the pcm composite and the only way of heat transfer takes place through heat conduction. Experiment were conducted to test the battery surface temperature at 5°C discharge rate and at 25°C of room temperature. The maximum temperature occurred in the middle of the battery than the battery surface temperature difference. The experimental values are agreed with the simulation results. The pcm is not fully melted and has the acceptable heat transfer co-efficient of 10 W/m²K. The more thicker the pcm plate, higher is its stability of the structure, more complex and also increases the cost. This system can provide the design guidelines for the bms and tms[30]. Wenfu Situ et al developed a pcm plates by using double copper mesh for the thermal management system in LiFePO₄ battery. In this study, a quaternary PCMP is made using the paraffin, expanded graphite and low density polyethylene, copper mesh with the air cooling system is experimentally and the results have been simulated. The purpose of this development is to increase the thermal conductivity, enhancing air cooling, and to reduce the internal temperature of the battery. The pcm is sandwiched to the prismatic batteries. The high thermal conductivity copper mesh can decrease the maximum temperature in the battery and disturbs the air surrounded by the battery to make the temperature uniformity and it also enhance the performance of heat dissipation. The dcm-pcm at an air velocity of 6 m/s have the excellent performance with forced air coupling. This system shows highest heat dissipation performance which reduces the extra energy consumption[31].

Abid Hussain et al conducted the thermal management experiment using the composite pcm, which consists of paraffin saturated with graphene coated nickel foam. By using graphene coated nickel foam, the thermal conductivity of paraffin has been increased. It is compared with the nickel foam, paraffin wax, graphene coated nickel foam, and nickel foam saturated with paraffin wax[32]. Minqiang Pan et al developed a cpcm based on cutting copper fiber sintered skeleton with paraffin to calculate the heat dissipation of li-ion batteries with both experimental and numerical method. Compared to air cooling, the temperature rise of this composite is lower than pure paraffin. This shows that copper has enhanced the thermal conductivity of pure paraffin. With the same mass fraction of copper, the temperature rise is low with cutting copper fiber sintered skeleton when compared to copper foam/paraffin composite. At the end of the discharge of the process, the temperature difference was not greater than 5°C and the other paraffin showed higher temperature difference. Thus this composite has enhanced the heat transfer and by transferring heat with higher to lower temperature regions. In the numerical simulations, the temperature of the pcm remained constant in the melting process and in experimental when the pcm melt, the temperature is increased slowly this difference is due to the simplification of the model in numerical methods and the temperature is not greater than 1°C. The heat rate of the battery pack decreased by increasing the spacing between the cells, it also increase the duration of phase change. The numerical model conducted is accepted to give the accurate results of the experiments. This numerical model can be used to investigate and predicts the pores per inches, battery spacing, battery temperature on air cooling heat transfer co-efficient. The experimental results agreed with the numerical and also serves as a validation for the numerical model. This serves as a application reference for the heat dissipation of li-ion batteries[33].

Wangzhou Yuan et al introduced silicon carbide into the SiC/EG with paraffin cpcm to increase the thermal conductivity of the cpcm module. Naturally silicon carbide has high thermal conductivity and electrical resistivity compared to EG. By applying silicon carbide into cpcm, the thermal conductivity is increased but its electrical resistivity decreased. Epoxy resin was also added to the cpcm for better machinability. Adding the 15% wt of SiC into cpcm, the volume resistivity is increased and its corresponding thermal conductivity is also increased, thus gives a better cooling performance. Continuous increase in this weight % of SiC and reducing ER contents lead to decrease in mechanical strength. 6 cpcms were formed with varying the epoxy resin and SiC based on the mass ratio with paraffin and EG. At higher temperature with longer period only small amounts of paraffin leaked from the cpcm. More paraffin leakage leads to unsafety. Under 2.5°C and 3.5°C, the cpcm with 50:3 ratio of PA/EG and 15% wt of SiC with 32% wt of ER shows better cooling effect[34]. Yi-Huan Huanga et al conducted an experimental and numerical methods to reduce the thermal contact resistance in the Li ion battery module by using flexible form stable cpcm. Eicosane and tetracosane are the two pcm and each pcm is added with the supporting material polymer obc and the additive to...
The thermal conductivity of the pcm module affects the battery pack temperature uniformity. The thermal conductivity increases with the packing density. The high heat removal rate is accomplished with high thermal conductivity. This heat removal is highly crucial when the heat density is very high. The best density and percentage of EG/paraffin composite is expressed as 850 Kg/m$^3$ & 920 Kg/m$^3$ and 85% & 75% by considering the leakage of pcm to be reduced[38].

Bohayra Mortazavi et al proposed a multiscale investigation based on composite for Li-ion batteries. The multi scale modeling techniques were used to predict the efficiency in thermal management of rechargeable batteries[39].

Guwen Jiang et al used a pcm to control the heat transfer rate in the tube-shell Li ion battery pack. The pcm is paraffin with expanded graphite. Forced air cooling was also coupled with the thermal management system for the solidification of pcm. The battery cells are wrapped with the pcm and it is surrounded by the aluminium tubes and baffles are fitted with the battery pack. The baffles used in the battery pack increase the air fluid heat transfer and changes the flow of air fluid direction. The tube shell battery pack with cpcm shows excellent temperature reduction in the single cell and the temperature difference was also low in the battery pack. The largest thermal management is achieved by using the pcm with 4 mm thickness. The heat dissipation efficiency of battery pack is increased by using the cpcm. By using the baffles the heat transfer of cooling air is improved. The system was executed both experimentally and numerically[40].
Jinghui Li et al. has enhanced the thermal conductivity of expanded graphite/paraffin wax by introducing silica gel with aluminium honey comb to improve the thermal management in LiFeO₂ batteries. The silica gel prevents the leakage of paraffin wax from the composite. The aluminium honey comb, improves and shows the highest heat dissipation efficiency from the pcm into the ambient air. This increase the phase transition time and shows a steadier heat dissipation rate from the batteries. The composite also exhibits the most attractive mechanical properties and after compression strength and toughness properties have been improved by using aluminium honey comb. And there is no cracks and deformation in the composite. This composite pcm is experimentally verified to operate at a maximum temperature of 50°C and also shows an efficient battery operation range. In this pcm, a slight difference in supercooling is observed which can increase the utilization efficiency of the cpcm[41].Morteza Alipanah et al. conducted a numerical investigation to examine the effective parameters on battery surface temperature, which affects the performance and lifespan of batteries by using the pcm’s and pcm with metal foam. The thermal management system is evaluated based on the battery surface temperature and its uniformity and compared using the pure octadecane, pure gallium, octadecane-aluminium foam composite. By using octadecane as cooling material in the battery, the battery surface temperature is uniform at low discharge rates than higher discharge. The uniformity tends to be decreased if the heat generation is increased and this effect is due to the higher convective heat transfer. The thicker the pcm used the discharge time can be increased within the maximum safety range due to the larger mass of the pcm. Compared to octadecane, the heat diffusion is higher in gallium due to the more uniform temperature distribution and longer melting time. The surface temperature of battery in solid and mushy zone remains unchanged when the heat fluxes is increased this is due to the higher thermal conductivity of gallium than octadecane. The battery surface temperature is more uniform by adding aluminium matrix to the octadecane due to the increase in thermal conductivity of octadecane. The battery surface temperature difference was greater in octadecane and in gallium and octadecane – aluminium composite it is negligible. The results reveal that the gallium and octadecane-aluminium composite can store the waste heat generated by batteries[42].

5.3.2 PCM with Carbon Fibre

Fereshteh Samimi et al. examined the heat transfer enhancement in the pcm containing carbon fibre. The discharge of li ion battery under the cooling medium of air, pcm and the pcm containing carbon fibre are simulated in CFD. The numerical validation results are compared with the experimental results from the literature. Natural convection will not remove all the heat generated in the battery, so some other cooling system should be employed to effectively remove the heat. Passive cooling method provides the extra thermal management by utilizing pcm as a coolant. The mass concentration is of carbon fibre is 0.69% as in experimental study. carbon fibres affects the temperature distribution and has an advantage of increasing the thermal conductivity. Adding carbon fibres into the pcm also affects the temperature distributions within the cell and the temperature distributions can be made uniform by developing the composites with the carbon fibre percentage higher. PCMs with higher carbon fiber have thermal conductivity enhancement factor constant and pcm with small amounts of carbon fibers show unsteady thermal performance. If the melting rate is higher, more liquefied pcm is available in the system for natural convection and the liquid velocity increases. The pcm cooling is better than air cooling but the only disadvantage is the low thermal conductivity of pcm. this issue can be replaced with the pcm with carbon fiber. The experimental and simulated results are in reasonable agreement to each of the obtained results[43].Farid Bahiraei et al. conducted an experimental and numerical models to investigate the thermal performance of li ion batteries by enabling carbon based nanostructures in the paraffin, thus increases the thermal conductivity of the paraffin. Three carbon based nano composites are prepared by using different carbon additives are carbon nano-fiber, graphene nano-platelets and graphite nano powder. With these the graphite based nano enhanced pcm shows the enhancement of latent heat thermal energy storage systems with mass fraction of 7.5% and 10%. This is due to continuous matrix and effective heat transfer path in the graphite based composites. The nano enhanced pcm samples revealed better temperature control in the process and suggest the optimal design of the battery module[44]

5.3.3 Heat Transfer Enhancement using Heat Pipe

Jiateng Zhao et al. used heat pipe to enhance the heat transfer in pcm. In this batteries are eliminated and the aluminium cylinders wrapped with heat films are used as a substitute to reduce the cost and improve the efficiency of experiment. The battery substitutes are wrapped with pcm and the heat pipes are embdedded with the cpcm made of expanded
graphite and paraffin with phase change temperature of 40°C. composite with 16% weight of EG is selected for its high latent heat. The test is also conducted with the air cooled btm which shows that increasing the inlet air velocity may decrease the temperature under 50°C. Maximum temperature of the module decreased at increased air velocity, but increasing more will not give any notable decrease. The thermal performance of pcm without HP was tested under natural convection. Then the HP is inserted in the module. After the insertion of HP into the pcm module, the temperature distribution is uniform before the phase transition of pcm is completed and the maximum temperature in the module is decreased. The PCM/HP tms was better than the air cooling system, because better cooling effect is obtained with the HP with the increase in phase transition process of the pcm\[45\]. Z.Y. Jiang et al established a numerical study to explore the cooling performance of pcm with the heat pipe during the charging and the discharging phase. One charge/discharge process is simulated in this process. Sandwich structure is proposed inorder to get the high efficiency and compact structure of the thermal module and it consists of li-ion battery, heat pipe evaporation section, pcm plate. To increase the heat transfer rate and temperature uniformity, a copper plate is welded to the heat pipe evaporation section. Copper fins are welded at the condensation section to enhance the heat transfer process. Two pcm with different melting point of 48°C AND 30°C is used. 5% EG is added with pcm to increase the thermal conductivity of the pcm. another two modules with and without pcm is also constructed. The pcm quantity is same in HP/PCM composite module and the module only with pcm. the three modules are wrapped by insulated cotton. For the simulation process, lumped thermal model for cooling is developed. The temperature of battery is higher in discharge process than the charging process. But the numerical results shows the slight variation of increase of temperature in the charging process, the reduction in temperature is due to the heat release rate is higher than the heat generation rate. The temperature of the battery module with pcm of 48°C and without pcm shows the maximum temperature when compared to another pcm because the pcm melts when the battery temperature reaches 30°C during the discharge stage, in this the pcm latent heat is not utilized and the battery remains at 30°C. The further increase in discharge makes the pcm to be fully melted and exhaust the pcm. contact thermal resistance also increased. To recover the latent heat of the pcm, additional convective cooling is to be added. The battery temperature of the module with hp pcm is lower than the pcm -2 due to the efficient heat released by the heat pipes and also can recover the latent heat of pcm in each cycle. The heat flux of HP is constant because the generation is equal to the heat release. The thickness ratio β, is based on the quantity of pcm used. β is taken as 0.37. a turning point thickness ration is founded as 0.17. increasing the greater than 0.17 decreases the temperature of the battery, decreasing β less than 0.17 makes the temperature of the battery nearly constant. It is suggested to keep the phase change temperature 3°C higher than the ambient temperature. In the solidification stage, heat pipe dissipates the heat generated from the battery and the heat released by the pcm. Heat pipe also lowers the heat flux by heat dissipation of HP/PCM\[46\].

5.3.4 Thermo Electric Generators Using PCM

De-Hai Yu et al developed a shape remodeled phase change materials for the thermal energy storage system. The shape-remodeled macropellets which consists of octadecanol as the core and the silicone elastomer for encapsulation was prepared through a cast molding method, which has high latent heat density. The copper nanoparticles were also added into the silicone composite for comparisons. This developed pcm macropellet used in the TEG module have the advantages of easy shape remodeling to increase the heat transfer efficiency during charging and discharging cycles. The TEG module can be supplied with necessary heat when needed, this is possible because the pcm macropellet can hold the thermal energy in the form of latent heat in advance. This developed pcm can be remodeled with customized shape with dynamic and repeated remodeling with large scale deformation\[47\]. S. Ahmadi Atouei et al experimentally investigated the tms for TEG systems using three different phase change materials placed in the aluminium box fitted to the hot side, cold side and in-between cold and hot side. The pcm’s are calcium chloride hexahydrate, paraffin wax, and mannitol. The results shows that TEG can produce more than 1V electrical potential for 30 minutes and after that heater shut off. This is two times longer than heating process. when pcm is applied on both sides of the TEG with the power of 100W for 15 minutes with 3 identical phases in the heater, the temperature can be maintained under 45°C in the cold side. In the hot side, even after removing external heat sources the voltage can be generated for longer time. This long-term voltage generation can be achieved with this temperature improvement by the TEG. The pcm heat sink used cannot need any cooling energy. This method can enhance the net power generation. When the input thermal power is high, the pcm box fitted on the hot side may protect them without failure in the module\[48\].
5.4 Hybrid Electric Vehicle Cooling System

Maan Al-Zareer et al designed a new battery pack cooling systems by using ammonia as the coolant and utilizes the low saturation temperature of the fuel based ammonia. In this pack, the batteries are immersed in liquid ammonia and it absorbs the generated heat and the vapors of liquid ammonia cools the other part of the battery that are not covered in liquid ammonia. This ammonia cooling method can be applied to the battery pack for its operating range and for better cooling even at higher discharge rate. This ammonia cooling method can be applicable only to hybrid electric vehicles[49]. Maan Al-Zareer et al also used the high heat transfer rate of boiling to cool the batteries and the coolant is HEV fuel which is propane. The batteries are submerged in the liquid propane which forms a pool. The generated heat in the batteries are absorbed by the liquid propane and the liquid begins to boil and evaporate and cools the batteries which are uncovered with propane. The simulation cycles carried are in the shape of a square wave with a period of 600 seconds. The effect of varying the battery spacing is also considered and states that the larger battery spacing can reduce the maximum temperature of the battery and also increases the temperature difference across the battery. It is suggested, that increasing the number of batteries, for long driving range, can reduce charging and discharging current which establish a better thermal performance. This is possible by reducing the battery spacing and increasing the number of batteries[50].

VI. CONCLUSION

Using the PCM can reduce the maximum temperature attained and maintain the operating range of the battery. The PCM selected should have stable form and leakage should be eliminated by using metal foams. Heat transfer characteristic can be enhanced by using the composite PCMs. The temperature reduction and temperature uniformity in the battery pack is attained using PCM and shows excellent TMS. The cost of pcm is also less compared to other conventional systems. The maintenance is also easy.

Highlights:

- The PCM technology is the more economical and non toxic to use.
- Excellent temperature controlling properties.
- Occupies less space than other cooling techniques.
- Utilisation of pcm in battery thermal management system can increase the life of the battery.
- Easy maintenance of Pcm.

Conflicts Of Interest:

There is no conflicts of interest.

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