Modeling and Study of Thermal Effects on Battery Pack Using Phase Change Materials

Umang Selokar

South Dakota State University

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MODELING AND STUDY OF THERMAL EFFECTS ON BATTERY PACK USING
PHASE CHANGE MATERIALS

BY

UMANG SELOKAR

A thesis submitted in partial fulfillment of the requirements for the
Master of Science
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MODELING AND STUDY OF THERMAL EFFECTS ON BATTERY PACK USING PHASE CHANGE MATERIAL

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Mechanical Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by candidate are necessary the conclusions of the major department.

Huitian Lu, Ph.D.
Thesis Advisor

Kurt Bassett, Ph.D.
Head, Department of Mechanical Engineering

Dean, Graduate School
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ABSTRACT

MODELING AND STUDY OF THERMAL EFFECTS ON BATTERY PACK USING PHASE CHANGE MATERIAL

UMANG SELOKAR

2019

The scope of the current research is to reduce the temperature distribution area in Li-ion cell and the battery pack with respect to time in battery design, using CFD technology (Computational Fluid Dynamics) in ANSYS fluent. A 3D model was design in CAD software (CATIA) and analyzed in ANSYS fluent to study the thermal behavior of the designed battery pack. An analytical thermal model was generated to evaluate the heat generation rate passing throughout the battery pack. The battery pack were analyzed and simulated on two different designs. One battery design is modeled with and without insulation (superwool EST compression paper) between the cells and the other design is with and without PCM (phase change material). We have two materials, general insulation with low thermal conductivity and PCM with high thermal conductivity to observe thermal behavior of the battery. The outcome of this analytical model was employed under the convective boundary conditions of the battery design in CFD simulation to identify the thermal behavior. The achieved results show the comparison between insulation and PCM that gives much more achievable performance of temperature distribution evaluation with PCM than that with insulation material, as PCM absorbs the rise in temperature and procrastinate to attain the defined maximum temperature with respect to time.
Simulation results carried under the convective temperature as for PCM at 310 K, 400 K, with different intervals of time on five-unit (5s2p: 5-in-series of 2-in-parallel). Temperature with insulation material model at 310 K, 400 K, on five-unit (5s2p: 5-in-series of 2-in-parallel). Heat created as a function of current $I$ (ampere) is passed through the tabs and throughout the center of each cell of the battery.

The phase change duration depends particularly on the density, thermal conductivity, specific heat of the PCM material. Phase change material can reject much heat from cell to environment. The purpose of the PCM design in battery is to limit the supply of heat, in time, to the PCM and thus extends the phase change duration and increase the heat transfer to the environment. The simulation shows the maximum temperature are reduced by employing PCM over the surface of the battery. PCM employed with thickness of 0.32 mm and insulation thick material of 3.125 mm.

We have employed two layers of PCMs on each surface of the cell to sustain the maximum temperature, double layer of PCMs on both surfaces of Li-ion cell will be more efficient than one surface. A thin PCM thickness around the cell, in turn, provides better temperature distribution due to heat generated in the cell.

When a PCM with high thermal conductivity is employed for Li-ion battery, the temperature dissipated becomes more uniform as compared to insulation material. The achieved results show the comparison between insulation and PCM that gives achievable performance of temperature distribution and reduces the initial rise, as PCM absorbs the heat and reduce temperature distribution area. The purpose of the PCM design in battery is to absorb the supply of heat, in time and thus extends the phase change duration and increase the heat transfer to the environment.
Introduction

1.1 Overview of Lithium-ion Batteries

In the 21st century, there is a rapid increase in the problems concerning with energy crisis and environmental pollution. Hence, lithium-ion batteries play the vital role as a recyclable energy source. During the initial days, in 1991, the SONY corporation commercialized Li-ion batteries which had advantages of high-power density, high output voltage, high energy density [1]. Li-ion battery consists of cathode, anode, electrolyte, separator. The electrochemical performance and the cost of a battery are determined by the active material of the cathode. LiCoO$_2$, LiMn$_2$O$_4$, LiNi$_{1-x-y}$Co$_x$Mn$_y$O$_2$, LiFePO$_4$ etc. are included in the mainstream of the commercialized positive electrodes. LiCoO$_2$ is recognized to be the earliest commercialized material, giving the advantages of simple preparation process, stable material properties and high energy density but it is disadvantageous in the cases of poor thermal stability and security risks [2-3]. LiMn$_2$O$_4$ has abundant resources, is priced low and performs well, but it has the disadvantages of low energy density, poor in terms of thermal stability and its crystalline structure can be distorted very easily. Therefore, it has poor high temperature storage performance and poor cycle performance. LiNi$_{1-x-y}$Co$_x$Mn$_y$O$_2$ sums up the advantages of three elements, which has the advantages of large specific capacity, outstanding cycle performance and moderate price of cost, while it has the disadvantages of poor material surface stability due to property of hard oxidation of divalent Ni. LiFePO$_4$ gives better cycle performance, the security is good enough, but it has low mix conductivity, low energy density and performance rate is poor [4].
1.2 Thesis Research Motivation

At present and since a few years, energy has become the most valuable and challenging aspect of the human existence. Great interest and tremendous efforts are being taken to generate, conserve and develop energy resources. Electrical energy is the most significant for power generation due to its wise and numerous applications. Due to the limitations on the conventional sources, emphasis has been given to alternative sources of energy. While catering this need there was the development of concept of phase change material as an alternative source of energy in the Li-ion batteries. Li-ion batteries coupled with other renewable energy sources like wind, solar etc. can prove to be a useful as well as clean source of power generation.

The world’s need to reduce the carbon emission and use to sustainable and highly reliable of renewable energy sources motivates this thesis. Important consideration for the spacecraft, electric vehicles, and satellites are energy storage and Thermal Management System for batteries are a part of the motto of this research.

A comprehensive literature review of previous research work on the estimation of the Phase Change Material (PCM’s) in lithium-ion batteries has been revealed to a further investigation on this topic is needed.

Though previous research work has proposed various estimation methods for PCM, most of them include solid and liquid-state PCM with ANSYS fluent, COMSOL Multiphysics, have been proposed to perform thermal behavior of Li-ion batteries.
Battery Thermal Management System (BTMS) has as one of the keys enables to improve system safety using PCM and superwool material, leads to increase the operations reliability, system life cycle cost, and prevent failure.

1.3 Thesis Objectives and Scope

This thesis scopes up to the creation of a model in CAD software and determine its thermal behavior by employing Phase Change Material (PCM) and Superwool (insulation) material and for the understanding of the thermodynamic system of the model by observing the melting time of both the material sand its stability with respect to time for both the materials at different temperatures (Kelvin).

The research objectives can be stated as follows:

The first and important objective is to model the Li-ion battery pack using CAD software (CATIA V5) with Phase Change Material and Superwool material as a 5s2p battery pack and import into ANSYS fluent and treat as a non-linear dynamic system, with discrete time state model. The nonlinear system of battery pack is used by ANSYS boundary conditions and its framework to assist the heat dissipation of PCM and Superwool in lithium-ion battery.

Phase change material to increase the remaining useful life (RUL) for lithium-ion batteries have become increasingly important. Prognostics and Health Management (PHM) has keys enables to improve system safety, increase system operations reliability, system life cycle cost, and prevent from failure by increasing the time to stable the uniform temperature distribution.
1.4 Overview of Thermal Management System

According to the difference in heat transfer medium, thermal management of lithium-ion battery can be divided into three types: phase change material cooling, air cooling and liquid cooling [5]. Among these three, first one is passive thermal management and the remaining two are the active thermal management. The external air enters into the inner channel of the battery pack at the time of air cooling. After the convective transfer of the heat on the surface of the battery and the flows out along with the air. Based on the spontaneity of the air flow, cooling can be divided in two types: free convective air cooling and forced convective air cooling. Free convective air cooling is defined as the natural convection caused by vehicle driving is. The heat transfer coefficient on the heat exchange surface is approximately 5 W/m * °C. Forced convective air cooling is driven by a fan to provide the flowing air. Its heat transfer coefficient on the heat exchange surface is about more than 10 W/m * °C. In the designing of the air duct, air cooling has higher demands, and the temperature consistency of the cell monomer is not optimal enough due to inconsistency in the flow field.

Fig. 1.1 Free convective air cooling [5]
The heat transfer medium circulated in a battery group is liquid is termed as liquid cooling means that the heat transfer coefficient of liquid is mostly larger than air and a thinner liquid boundary layer that makes thermal conductivity higher than that of air. Accordingly, the liquid is directly contacted with the battery, the liquid cooling is divided into two types; direct-contact cooling and indirect-contact cooling. The heat transfer medium in direct-contact cooling is insulating mineral oil. Generally, water and ethylene glycol act as heat transfer medium in indirect-contact cooling. Indirect-contact type liquid cooling should ensure liquid pipeline to have good sealing performance and in order to achieve good effect of temperature control it should ensure that the direction of pipeline is reliable. Hence, indirect-contact type liquid cooling has scope and demands the battery box design and processing. Highly viscose mineral oil is used in direct contact type liquid cooling, which means it needs a larger pump power for the operation, which is very uncertain for the driving range of electric vehicle whose driving range is already insufficient.
Above introduction is capable to predict the deficiencies of the battery thermal management:

(1) It occupies large space, needs for mechanical additional power is required to operate them and the system is complex.

(2) The heat released by the battery cannot be recycled, it only damages the battery. It has been always attempting to achieve energy saving and reduction of emission. The thermal management system with PCM material cooling is to absorb the heat of the battery by latent heat of PCM material by the phase change process and prevent the battery temperature from rising too fast. PCM’s are able to act as energy storage sinks [6]. It reduces the temperature difference between monomers, and it helps the storage of energy in cold environment, and it also transmits the energy into the battery for achieving the thermal insulation effect and improve the battery performance when the environment is cold. With the perspective concerning to save energy, the PCM based thermal management system of
lithium-ion battery leads to better cooling effect and thermal insulation effect. The passive thermal management of battery proves that it can maintain the thermal stability of the current in commercial chemical batteries and is able to reduce the expensive new product line.

1.5 Battery Thermal Management System with Phase Change Materials

Thermal management systems on the surface of the battery are based on heat transfer, similarly, to mitigate the temperature rise in the center of battery and balk the degradation process of materials. The intrinsic thermal properties such as latent heat per volume of the battery and the ability to effectively shuttle heat away by the convection of air from the battery surface. The battery packs and its application decide to use active thermal management or passive thermal management systems in a battery. Such as man-pack electronics and electric driven tools it uses active thermal management systems are efficient to transfer heat away from the battery surface, size occupies a large amount of space. Passive thermal management systems that are PCM based provide concise in construction which mitigates the demand for mechanical devices and doesn’t require additional power to operate them.
Phase change materials (PCM) also known as Latent Heat Storage Materials (Phase change materials) are based on phase change transforming states of substances for the absorption or the heat release when the temperature is relatively stable. Latent heat i.e. the enthalpy of fusion, leads to thermal energy which is demanded for a given amount of mass of material to go through a phase transformation, and units represented in J/g. The latent heat storage materials can experience different types of transformation such as solid to solid transformation, solid to liquid transformation, or liquid to gas phase transformation. PCMs can be used as inorganic compounds, organic complexes, or eutectic complexes [7]. Thermal energy will be absorbed by utilizing in changing the material to another phase as soon as the temperature elevates up to the phase change temperature of PCMs, temperature is kept in a relatively constant range according to this (Figure 1.4) under the condition of a fixed heat flow rate, the time length of the temperature upland as shown in the temperature profile is dependent not only on the specific enthalpy of fusion of the material but also the
utilized mass of PCM [8]. Inorganic PCMs like salt hydrate holds a high enthalpy of fusion and large thermal conductivity, its obvious disadvantages include, restricted melting/freezing cycles, corrosive, electrically conductive, and suffer from supercool. The PCMs which are organic, (like paraffin waxes) are more suitable for battery systems in order to achieve larger than 1,000 melting/freezing cycles easily without severe degradation of process. The above-mentioned property is useful to the crucial demand of discharging/charging cycles applied for the present commercial batteries [9]. For solving these problems, it has demonstrated reasonable strengths and benefits for organic PCMs and capable of mitigating the temperature elevation of core in battery during high discharge rate with current lithium-ion batteries [10].

1.6 Organization of the Thesis

This thesis is divided into 5 chapters.

Chapter 1: Overview of thermal management system, Thesis Objectives and Scope, Thesis motivation, Research statement, Battery thermal management system with phase change materials and Organization of the Thesis are discussed.

Chapter 2: A literature review of working principle of lithium-ion battery, battery modeling techniques, Phase Change Material on battery thermal management system.

Chapter 3: A Battery pack of 5s2p (5-unit) is modeled in CAD software and import into ANSYS fluent. Identified the model parameters with current in the form of thermal heat, implemented PCM and Superwool properties, defining boundary conditions for thermal estimation of both material, and simulation results and case study for the PCM are described.
Chapter 4: Comparison of PCM and Superwool with respect to temperature-time graphs, requirement of melting and uniformity in materials, and discussion are presented and recommendation for future research works are also provided.

Chapter 5: Result and Conclusion has discussed.
2 Literature Review

2.1 Mathematical equations for heat generation, SOC

A calorimetric method or a mathematical method are used to determine the heat generation in the cell.

\[ \dot{q} = I \left( U - V - T \frac{dT}{dT} \right) = h_s A (T - T_{amb}) + M_{cell} C_p \frac{dT}{dt} \]  \hspace{1cm} (2.1)

Here, U and V are open circuit or electromotive force and cell potential, respectively. \( h_s \) is per-cell heat transfer coefficient. The term \( I (U - V) \) is the heat generation due to heat polarization and \( (-IT \frac{dT}{dT}) \) is the entropy coefficient due to reversible process in the cell. \( M_{cell} \) is mass of the cell and \( C_p \) is the weight-averaged value of cell heat capacity. If we found the heat generation uniform in the cell, then heat generation per unit volume is given by [11].

\[ \dot{q} = \frac{I}{V_b} \left[ (U - V) + T \frac{dT}{dT} \right] \] \hspace{1cm} (2.2)

Where, \( \dot{q}, V_b, U, V \) and \( I \) are volumetric heat generation rate, battery volume, open circuit potential, cell potential and current respectively (> 0 for discharging and < 0 for charging). If heat generation includes reversible or irreversible effects, reversible heat released or absorbed in cell by chemical reaction is given by [11].

\[ Q_{rev} = n_{cell} T \Delta s = T \left( \frac{\partial U}{\partial T} \right) \] \hspace{1cm} (2.3)

In order to conduct numerical heat transfer analysis using ANSYS FLUENT software there should be mathematical model which shows the physics of the problem, governing equations, input variables and the relationship through these parameters. It concerns with
the initial and the boundary conditions and its valid range of variation with the governing equations. Moreover, this model is determined to achieve the objectives for the problem by assigning the constraints and defining the related methodology.

For ANSYS fluent based simulations, initially the physical model has been modeled in CAD software (CATIA-V5), then it has imported and presented in ANSYS. Moreover, the insulation material and PCM is followed by the governing equations in the boundary conditions and in the cell zone which are employed and discretized by numerical methods. The model required the initial and boundary conditions to accomplish the formulation for simulation and are also illustrated. Fig. 2.1 shows the cell geometry and the aspect ratio lithium ion cell and surrounding the PCM. The heat generation rate is assumed to be the only heat source in the cell zone. The boundary conditions around the cell and positive/negative tabs which are connected to the cell are defined under free convection. Moreover, various thicknesses of PCM are considered and studied, and the cooling effectiveness is introduced to assess the BTMS (Battery Thermal Management System) and its performance considered in the study.
For this heat transfer problem, free convection is introduced in all surfaces including the cell and the PCM surfaces with ambient air. Numerical simulations are performed based on the finite volume methods, in order to obtain the thermal behavior of the cell and PCM. Under the governing equations, the differential form is integrated over each control volume, the variable to be studied is set in the center. The cell centroids variables are interpolated to have profiles for variations for temperature with refer to time. The discretized resulted equation is reflected in the domain. Once obtain the discretized equation, an algebraic solver is used to determine converged solution.

A partial differential equation is described which comprises diffusion term, convection term, transient term and source term. By taking all these term into account, a general equation can be derived:

$$\frac{\partial}{\partial t} (\rho \theta) + \nabla \cdot (\rho \bar{u} \theta - \Gamma_\theta \nabla \theta) = s_\theta$$  \hspace{1cm} (2.4)

Where, $\theta$ is 1 for continuity and energy equations, respectively. $\Gamma_\theta$ and $s_\theta$ are the diffusion coefficient and the source terms which have consistent units. For melted PCM in the
simulation domain momentum equation is not considered. The energy equations are the governing equations which analyze the temperature distribution and heat transfer in the model. The maximum shift in the location of the critical rake in the cell is given by the PCM effect. The nature of the current study is dependent on transient behavior of the system. The PCM has been melted and the thermal conductivity will determine the effective in the solution.

The temperature rises in the two different critical rakes for the case with no PCM and when there is 3 mm PCM around the cell. Observations say that after 10 to 20 min, the PCM has prevented temperature increase in the cell. The upper end of the cell has the maximum temperature distribution. The PCM is melted by increasing the temperature. The amount of PCM used will extend the time interval that temperature is absorbed in the PCM and prevents the temperature increase. When the PCM is employed in 3 mm thickness around the Li-ion cell, the temperature distribution becomes 10% more uniform. By increasing the PCM thickness around the cell, the location of maximum temperature moves inward the cell. Without the PCM, the location is closer to the bottom side of the cell. A large PCM thickness around the cell will have larger depth in curvature which, in turn provides better cooling in cell [11].

- Heat generation due to contact resistance:

Heat generation in the cell and the battery pack can be calculated by modeling numerically or by using the calorimetric method. Parameters concerning with phase change temperature inside the cell, PCM, joule heating, electrochemical reactions and change in temperature with insulation material will change the heat generation whereby the cells surface
temperature. The following energy balanced equation is used for the heat generation due to its contact resistances and the values are calculated from Equation (1) [12]:

\[ Q_c = \frac{I^2 R_p}{A} \]  \hspace{1cm} (1)

Here, \( R_p \) and \( A \) are the internal resistance and the total surface area of the cell respectively. \( Q_c \) is the heat generated due to contact resistance. \( I \) is the current in ampere which is directly proportional to the heat generated.

- State of charge (SOC)

The SOC of the battery or battery pack is defined as the ratio of remaining charge capacity \( Q(t) \) at any given time \( t \) to its total usable capacity \( Q_{total} \) when fully charged, and it is represented by

\[ SOC(t) = \frac{Q(t)}{Q_{total}} \]  \hspace{1cm} (2.5)

Accurate SOC estimation can maximize the performance of the battery and protect the battery to prevent overcharge and over discharge. SOC, provides a measure of the amount of electric energy stored in a battery. It is analogous to fuel gauge on a conventional internal combustion engine vehicle [13]. The SOC is a dimensionless number between 0 and 1 representing in a percentage. It has noted that a zero SOC does not mean that the battery is full empty, only that the battery cannot be discharged anymore without causing permanent damage (irreversible chemical reaction) to it [14].
• State of Health (SOH)

The mathematical definition of SOH is not easy and differs for different applications one of the commonly adopted equations is defined as [15]:

\[
SOH(t) = \frac{Q_{total}(t)}{Q_{new}}
\]  

(2.6)

Where \( Q_{total}(t) \) is the instantaneous total capacity at any given time \( t \), \( Q_{new} \) is the capacity of new battery, and it starts to decrease as a function of time when the battery is being used. As there are many parameters involved in comprehensive algorithms, so the estimation of \( Q_{total} \) over time is not simple. A condition which defines the battery life between the beginning of life and End of Life in percentage defines the State of Health (SOH). The beginning of the life of a battery is defined as the point in time when battery life beings. The end of life of a battery is reached when the battery cannot perform according to its predefined minimum requirements.

2.2 General Operational Principle of Lithium-ion Battery

G.N. Lewis began remarkable work on lithium-ion battery in 1912, but it was not until the early 1970s that the first non-rechargeable lithium batteries were made commercially available. To develop rechargeable lithium batteries in the 1980s many attempts failed due to instabilities in the anode material which was made by using metallic lithium. (The metal-lithium battery uses lithium as anode; Li-ion uses graphite as anode and active materials in the cathode.)

Lithium batteries are grouped into two categories due to high energy densities in lithium batteries than legacy batteries (up to 100 times higher): Primary and Secondary batteries.
- Primary (non-rechargeable) lithium batteries are made up of single-use cells containing metallic lithium anodes. Non-rechargeable batteries are considered throughout the industry as “Lithium” batteries.

- Secondary (rechargeable) lithium batteries comprise of rechargeable cells which contain an intercalated lithium compound for the anode and cathode. “Lithium-ion” batteries are the common name used for rechargeable lithium ion batteries. Single lithium-ion batteries (also referred to as cells) have an operating voltage (V) that ranges from 3.6 - 4.2V. Lithium ions move from the anode to the cathode during discharge. During charging the ions reverse direction. The “chemistry” of the battery is defined by the litigated metal oxide or phosphate coating on the cathode. Lithium-ion batteries have electrolytes that are typically a mixture of organic carbonates such as ethylene carbonate or diethyl carbonate. The flammability characteristics (flashpoint) of common carbonates used in lithium-ion batteries vary from 18 to 145 degrees C. There are four basic cell designs; button/coin cells, polymer/pouch cells, cylindrical cells, and prismatic cells [16]. (see Figure 2.2)

Fig. 2.2 Typical cell design [16]
The battery cell voltage is calculated using the energy of chemical reaction taking place inside the cell. It is the work of chargeable battery to convert chemical energy into electrical energy and vice versa. The positive and negative electrode are referred to as the cathode and anode respectively. The basic setup of a battery has three main divisions: the positive electrode, the separator, and the negative electrode., as shown in Figure 2.1. The battery is connected to an external load using current collector plates. In case of Li-ion cells, a copper collector is used for the positive electrode [17].

![Figure 2.3: Electrochemical functionality of a battery during charging (a), Discharging (b) [17].](image)

The anode composite material defines the name of the Li-ion battery and is usually made up of a mixture of carbon, while the electrolyte can be made of liquid, polymer, or solid materials. The anode is the electrode capable of supplying electrons to the load. In case of solid or polymer material, the electrolyte act as a separator.

The material properties are taken from Kim’s papers [4] and [3]. The computed material properties for the battery cell presented in the simulating are shown in the following table.
Table 2.1: General properties of the battery cell

<table>
<thead>
<tr>
<th>Zone</th>
<th>$P_c$ [um]</th>
<th>$P_e$ [um]</th>
<th>S</th>
<th>$N_e$</th>
<th>$N_c$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta$ [um]</td>
<td>20</td>
<td>150</td>
<td>12</td>
<td>145</td>
<td>10</td>
<td>322</td>
</tr>
<tr>
<td>$\rho$ [Kg/m$^3$]</td>
<td>2700</td>
<td>1500</td>
<td>1200</td>
<td>2500</td>
<td>8960</td>
<td>2092</td>
</tr>
<tr>
<td>$C_p$ [J/Kg-K]</td>
<td>900</td>
<td>700</td>
<td>700</td>
<td>700</td>
<td>385</td>
<td>678</td>
</tr>
<tr>
<td>$K$ [W/m-K]</td>
<td>238</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>398</td>
<td>18.2</td>
</tr>
<tr>
<td>$\sigma$ [s/m]</td>
<td>3.83e7</td>
<td>13.9</td>
<td>100</td>
<td>6.33e7</td>
<td>$\sigma_p = 1.19e6$</td>
<td>$\sigma_n = 9.83e5$</td>
</tr>
</tbody>
</table>

The separator being a porous membrane helps to transfer of lithium ions only, thus serving as a barrier between electrodes. It also prevents the occurrence of short-circuiting and thermal runaway while at the same time offering negligible resistance. The cathode is the electrode usually made of metal oxides (ex. LiCoO$_2$ or LiMn$_2$O$_4$) as shown in (Figure 2.4).

Figure 2.4: Electrode reaction of a battery during [18]
Oxidation reaction takes place at the anode where the trapped lithium particle starts to deintercalated or diffuse towards the electrolyte-solid interface splitting lithium ion into ions and electrons move through the solution due to the potential difference while the electrons moves through the current collector because the electrolyte solution acts as an electronic insulator [18]. In presence of a load current, (Reduction-oxidation) redox reaction occurs. Reduction reaction takes place at the cathode where the traveling lithium ion from the anode starts to intercalate and react with the electrode happens without a change in the electrode crystal structure “Intercalation” mechanism. The whole phenomenon of intercalation and deintercalation is reversible as lithium ions pass back and forth between the electrodes during charging and discharging [19]. Unfortunately, due to cell material degradation and other irreversible chemical reactions, the cell capacity and power degrade with the number of cycle and usage [20].

2.2.1 Fundamental Models

A battery cell’s behavior is usually described by the “fundamental” models, beginning from its physical foundation principles. The literature on fundamental models is quite extensive [21] for a review of the work proposed in the last two decades. Fuller, Doyle and Newman developed the first approach to model Li-Ion with two composite electrodes and a separator at the University of California, Berkeley in the first half of the 90s. A literature review of this topic that most of the modern models are the derivatives of the original work which is considered a milestone for the argument. In their original works [22] and [23], Fuller et al. modeled the galvanostatic charge and discharge of a dual lithium ion insertion cell, shown in Figure 2.5.
Figure 2.5. Dual-insertion cell sandwich consisting of composite negative and positive electrodes and separator. [22].

This model which could be used to simulate any cell utilizing two composite electrodes composed of a mixture of active insertion material, electrolyte, and inert conducting material. In particular, the diffusion in the solid material will be assessed since it is considered to be a strong limitation in some cells. Physical properties related to the concentrated solution theory allows one to deal with the transport phenomena. Following this approach, the driving force for mass transfer is the gradient in electrochemical potential given by

\[ c_i \nabla \mu_i = K_i (v_j - v_i), \quad j \neq i \]  \hspace{1cm} (2.2.1)

where \( c \) is the concentration of species [mol/l], \( \mu \) is the electrochemical potential of species [J/mol], \( v \) is the velocity of the species [m/s] and \( K \) is the frictional coefficient describing the interaction between species \( i \) and \( j \) [Js/m^2]. The total current flux \( I \) is uniform and flows through either the insertion material phase \( (i_1) \) or the electrolyte phase \( (i_2) \). Since the current in the two phases is conserved, it can be stated that
\[ I = i_1 + i_2 \] (2.2.2)

The current flowing in the matrix is governed by Ohm's law:

\[ i_1 = -\varsigma \nabla \Phi \] (2.2.3)

where \( \sigma \) is the conductivity of the solid matrix [S/cm²] and \( \Phi \) represents the electric potential [24]. On the other hand, the variation of potential in the electrolyte can be written as:

\[ i_2 = -k \nabla \Phi + (kRT/F)(1 + \partial \ln fA/\partial \ln c)(1 - t_0) \nabla \ln c \] (2.2.4)

where \( k \) is the reaction rate constant, \( c \) is the concentration of electrolyte, [mol/dm³], \( fA \) is the activity coefficient of salt, \( T \) is the temperature, \( F \) and \( R \) are the Faraday’s and universal gas constants, respectively, and \( \Phi_2 \) has been measured with a lithium reference electrode in solution. According to the authors, a material balance on the electrolyte gives:

\[ \epsilon (\partial c/\partial t) = (\nabla \epsilon D \nabla c) - (i_2 \nabla t_0/z + v + F) + (aj (1 - t_0) / v) \] (2.2.5)

where \( \epsilon \) is the volume fraction of the electrolyte, \( D \) is the diffusion coefficient [cm/s], \( z \) is the capacity ratio between positive to negative electrode and \( jn \) is the pore-wall flux across interface [mol/m² s].

\[ jn = -DS. (\partial cs/\partial r) atr = Rs \] (2.2.6)

The boundary conditions for such equations can be derived from the condition that the flux density of each ionic species must be zero at the ends of the cell. In that point it is possible to infer also that the current flows only in the solid matrix \( (i_2 = 0) \).

As the diffusion coefficient of the inserted lithium ions has been here assumed to be constant, this is a linear problem and it can be solved by the method of superposition.
brief, the flux at the surface of the insertion particles can be calculated from the prior surface concentrations and a series of coefficients which are calculated separately. The open-circuit potential of insertion materials varies with the amount of lithium inserted and is expressed by a general function of concentration in the particle:

\[ U = U_\theta - U_{ref} + (c_s) \]  \hspace{1cm} (2.2.7)

where \( U \) is the open circuit potential, \( c_s \) represents the concentration of lithium in the solid particle phase and the function \( F(c_s) \) can vary widely depending on the insertion chemistry of the material. When developing this model, one must consider that universally accepted values of the lithium ion transference number and salt diffusion coefficient do not exist in the literature. In their works [25,26] the authors proposed some results that allow for a better comprehension of the problem.

2.3 Humanistic Approach

Models providing a representation of the input/output relationship of a system without investigating the fundamental physics are referred to as ‘humanistical’. These models are completely different as compared to the previously analyzed fundamental models, which describe the behavior of a battery cell which begins from its physical foundations principles. Control oriented models (COM) are lower order dynamic models (linear or quasi-linear) that are used to design control algorithms among phenomenological models. Examples of phenomenological models are the equivalent circuit models. Quoting [27], the equivalent circuit model is a simple structure, it still captures sufficient dynamics under both temperature and SoC variation, in this way it makes it applicable for use with real-time model-based estimation algorithms in automotive applications. For the modelling of the electrical part of batteries equivalent circuits are often used. They consist of a series of
Randle circuits, as shown in Figure 2.6. By piecing together multiple RC circuits, one is essentially providing a piecewise constant approximation of the frequency response amplitude.

Electrochemical studies often use Randle circuits. An active electrolyte resistance $R$ in series with the parallel combination of the double-layer capacitance and an impedance of a Faradaic reaction are present in them.

![Figure 2.6. Sketch of an nth order equivalent circuit to model the electrical dynamic of a battery [27]](image)

In [28] a first-order equivalent circuit model with parameters scheduled on SoC and temperature is presented. SOC is an approach related to the electrical model. Figure 2.7 depicts the electrical equivalent circuit. The simple first-order model is able to adequately compute the voltage-current relationship of the battery over a wide range of operating conditions due to the SOC and temperature scheduling of the open circuit voltage $E_0$, internal resistances $R$ and $R_0$, and capacitance $C_0$. 
The electrical model equations obtained using Kirchhoff’s current law, are reported in equations (2.3.1) and (2.3.2) [28]

\[ V_c = - \left( \frac{1}{R_0 C_0} \right) c + \left( \frac{1}{C_0} \right) I \]  

(2.3.1)

\[ V = E_0 - IR - V \]  

(2.3.2)

The input to the electrical modeling circuit is the current, \( I \), and the output is the battery terminal voltage \( V \). Note that, in this model, the total pack voltage is obtained by scaling a single cell voltage by the number of cells.

The SoC dynamics are determined through Equation (2.3.3)

\[ \frac{d\text{SoC}}{dt} = -\frac{t}{C_n} \]  

(2.3.3)

where \( I \) assumed to be positive during the discharge and \( C_n \) is the nominal capacity of the pack.

In automotive applications, control-oriented models are used by the management system to optimize the performance of the vehicle and of its components. Control-oriented models of batteries are composed, as shown in Figure 2.8, by two sub-systems:

- The electrical model
- The thermal model
The electrical part of the battery is normally modeled through an equivalent circuit with parameters (as the internal resistance and the open circuit voltage) scheduled with respect to SoC and temperature. The SoC is computed with a current based estimation, according to:

\[
\text{SoC}(t) = \text{SoC}_0 - \int_{t=0}^{t} \left( \eta I(t) / C_n \right) \, dt = 0
\]

(2.3.4)

Where, \( C_n \) is the nominal capacity of the cell, \( \text{SoC}_0 \) is the initial state of charge and \( \eta \) is the Coulombic efficiency of the cell, here supposed to be equal to 1[29]. The performance of batteries strictly depends on the internal temperature field [30], thus the electrical model is coupled with a lumped thermal model. In this model the battery is assumed to be a lumped body cooled by convection with a known heat transfer coefficient \( h \). The model predicts the uniform temperature of the battery starting from the ambient temperature \( T_\infty \) and solving the general heat balance.

\[
\frac{dT}{dt} = \frac{Q - Ah(T - T_\infty)}{mc}
\]

(2.3.5)
Where, \( Q = RL^2 + \sum_{i=1}^{N} Ri I_i^2 \) is the heat generated inside the battery, in [W]. \( Q \), is the total heat transfer rate. The battery dynamic is modeled through an equivalent circuit of order \( N \) and the subscript \( i \), referred to the current and the resistance, indicates that those quantities are referred to the \( i^{th} \) Randle circuit. \( m \) is the mass, and \( c \) is the specific thermal capacity of the entire system [J kg K].

After the temperature and SoC calculation, the model computes the open circuit voltage, the internal resistance and the capacity and resistance of the Randle circuits. These parameters are normally scheduled as function of temperature and SoC using different algebraic functions for charge and discharge processes. The model is simple and suitable for control-oriented and on-board implementation. From an electric point of view the accuracy is sufficiently high, as reported in [31]. From a thermal point of view, however, the model is inaccurate since the temperature distribution within the battery cell has been completely disregarded. Since the performance, optimization of battery module and cells are mainly affected by the operating temperature it is a crucial point to improve this aspect of these simplified models. Very accurate models of both electro-chemistry and heat diffusion inside a battery are performed with finite element software, like ANSYS® or COMSOL® However, these software applications are so memory and time consuming that there is no possibility for any on-board or real-time application. In this thesis a modeling approach to account for the temperature dynamic inside a li-ion battery cell, suitable with a control-oriented approach, will be developed.
2.4 Thermal Characterization

2.4.1 Single Cell Thermal Models

Newman and Pals [32] presented an extension of the work proposed in 1993 by Fuller and Doyle [33], to introduce an energy balance for a battery cell as their first work. In the previous models, a uniform temperature was assumed throughout the cell, although the temperature was allowed to vary with time. In this work a 1D thermal model has been introduced. Thermal modeling is particularly important for Li-ion batteries as the heat produced during charge and discharge may cause either irreversible side reactions or it might badly damage and even melting of the solid lithium. This is an important primary safety concern for the manufacturer of the battery. The energy balance used in [34], and first introduced by [35]:

\[ Q = (V_{oc} - V - T \frac{\partial V_{oc}}{\partial T}) = h_{conv}(T - T_{\infty}) + m_c c_p \frac{dT}{dt} \]  

(2.4.1)

where \( m_c \) is the cell mass per unit area [g/cm2]. The term \( I (V_{oc} - V) \) is the heat produced due to cell polarization, and the term \( -IT (\partial V_{oc} / \partial T) \) is due to the reversible entropy change in the cell. Isothermal modeling is important because it helps one understanding the operation of the battery at different temperatures. At higher temperatures, the cell potential is higher for a given value of active material utilization. The cell also utilizes more of the active material at higher temperatures.

The heat-generation rate as a function of time and utilization is given in Figure 2.9 for the same simulations. This figure demonstrates that the heat generation rate is much larger for lower temperatures than it is for higher temperatures. This result may also be seen by examining the cell-potential behavior: The heat generation rate is equal to the product of the current density and the difference between the open-circuit potential and the cell
potential. At lower temperatures, the conductivity is lower, and the larger ohmic drop leads to larger heat generation rates.

Figure 2.9 Heat-generation rate as a function of utilization and time for isothermal discharge of the cell at $I = 1.1$ mA/cm$^2$. [34].

For design purposes, it is useful to examine the temperature dependence of the energy and average power densities that the system can provide.

Figure 2.10. Specific energy and average specific power of the cell as functions of temperature for isothermal, galvanostatic discharge at $I = 1.1$ mA/cm$^2$ [34].
At lower temperatures, from 80°C to 100°C, the specific energy increases steadily as the cell attains a higher utilization with increasing temperature. Then, at temperatures from 100°C to 120°C, the energy density continues to rise, but at a slower pace, as the cell is reaching nearly 100% utilization. Above 120°C the specific energy begins to level off to its theoretical value. In this paper, adiabatic discharge behaviors are also presented: adiabatic modeling is important because it simulates the consequences of no heat removal, for example, if the temperature control system fails.

In [34] it is also anticipated that the one-cell model can be used to analyze the behavior of a cell stack under heat-transfer conditions by defining an appropriate per-cell heat-transfer coefficient for each cell in the cell stack. The authors consider 1D heat transport in the direction perpendicular to cell layers. This assumption is valid when transport in the direction parallel to cell layers can be neglected, such as when the cell stacks are very thin, or when the ends of the stack perpendicular to cell layers are insulated.

To use the one-cell model for cell-stack calculations, the per-cell heat transfer coefficient \( h_s \) must be related to the convective heat transfer coefficient.

\[
\frac{1}{h_s} = \frac{1}{2K_{cell}I_{cell}} \left[ \left( \frac{L}{2} \right)^2 - x^2 \right] + \frac{L}{2h_{conv}I_{cell}} \tag{2.4.2}
\]

Now that the per-cell heat transfer coefficient has been related to the convective heat-transfer coefficient, the temperature and discharge behavior for each cell in the cell stack can be calculated from known values of the convective heat transfer coefficient and from cell properties. The one-cell model proposed by Newman and Pals could be used to estimate the temperature and discharge behavior of the battery when the cell-stack temperature gradient can be neglected.
2.4.2 Battery Pack Thermal Models

When scaling up the smaller batteries, the thermal characterization of a whole battery pack is even more important, the internal heat generation increases which leads to the temperature rise and the occurrence of an uneven temperature distribution takes place in the battery. According to [36], battery pack performance in an automotive application directly affects the all-electric (zero-emission) range, power for acceleration, fuel economy, and charge acceptance during energy recovery from regenerative braking. Hence, all the parameters affecting the battery pack should be mandatorily optimized. The battery operating temperature range varies depending on the electrochemical couple used. Usually because of increased electrochemical reaction rates, higher temperatures improve the battery's performance. Elevated temperatures increase corrosion promoting the aging of the battery, so, the battery's lifetime decreases. Temperature profiles’ prediction is really very important for designing a thermal management system for the battery, and predict how the temperature variation in the battery affects its performance. An overview [36] of heat generation in battery modules is presented. With respect to the earlier statement, heat is generated within a cell by two effects: entropy change from electrochemical reactions and Joule’s effect caused by current flux. Practically EV and HEV rates, the first term (reversible entropy change) are usually smaller when compared to the second one (Ohmic and other irreversible effects). Thus, the heat is generated and released from the cell not only while charging but also at the discharge process.

Heat is either removed/rejected to the surrounding area as soon as it is generated in a module or it gets accumulated in the module, or when both happens. Another possibility is
that if the surrounding area’s temperature is higher than the module’s temperature, heat will be transferred into it. An overall energy balance on a battery module leads to:

\[ Q - h_b A_b (T_{bs} - T_f) - \sigma \varepsilon F_{bs} A_{bs} (T_{bs}^4 - T_f^4) = m_b c_b \frac{dT_{batt}}{dt} \]  

(2.4.3)

where:

- \( h_b \) = Convective heat transfer coefficient between battery surface and its surrounding fluid \([W/m^2K]\);
- \( A_{bs} \) = Battery surface area exposed to the surrounding;
- \( T_{bs} \) = Temperature of the battery surface;
- \( \sigma \) = Stefan-Boltzmann constant \((5.67 \cdot 10^8 [W \, m^2K^4])\);
- \( \varepsilon \) = Battery surface emissivity;
- \( F_{bs} \) = Shape factor between the battery and its surroundings;
- \( C_b \) = Weighted-average module heat capacity \([J/kg-K]\).

The radiative term (the third one) is usually small compared to the convective term (second one) if temperatures are below 100°C, so it is disregarded for common battery applications.

In Equation (2.4.3), an average battery temperature has been considered. However, in reality, a three-dimensional temperature distribution exists in the module. A commercial finite element analysis software has been used by the authors to solve for temperature distribution in HEV modules. The overall energy balance can be used to obtain the temperature distribution in a pack of modules. For example, if a certain amount of a fluid is passed around a module, the fluid temperature change can be obtained from overall energy balance for the module:

\[ h_b A_b (T_{bs} - T_f) = m_f c_f (T_{out} - T_{in})_{fluid} \]  

(2.4.4)
The overall temperature change in the fluid can be obtained from the overall energy balance:

\[
(Q - m_b c_b \frac{dT_{batt}}{dt}) = [m_f c_f (T_{out} - T_{in}) - m_f c_f \frac{dT_f}{dt}] \text{_pack} \tag{2.4.5}
\]

where \(N\) is the number of modules in the path of \(m_f\).

The second terms on each side of the equation are thermal inertia of the module and the fluid, respectively, and could be ignored for short-term transient and steady state cases.

To obtain thermal performance in modules and packs, the author proposes to use finite element analysis, to solve the two-dimensional or three-dimensional transient or steady state heat conduction equation for a set of modules at the beginning of the pack. If the interest is limited to the average battery temperature, conduction can be ignored, assuming a single temperature for the modules. It is possible taking advantage of symmetry to solve for the minimum number of modules or even sections of a module to reduce computational efforts.

Using an iterative process, the energy balance between the module surface temperature and its surroundings has been used to find the overall temperature change in the fluid. Temperature distribution in any module in the pack could be obtained by using the superposition principle and overall energy balance. For the analysis, the authors used a prismatic, valve-regulated, lead-acid battery module shown in Fig. 2.11.
In this analysis, an air flow cools a series of 10 battery modules, as depicted in Figure 2.12. The air temperature rises by 1.3°C as it passes by each module, resulting in a variation of 13°C between the inlet and the outlet.

There is also a variation of about 4.5 °C within each battery module. Although this cooling arrangement is not ideal, it is much better than placing the pack in a closed box, as shown in Figure 2.13.
Obtaining thermal images of a battery module or a pack is a useful way to obtain information on temperature variation and compare that with analytical results. It is more productive and less intrusive than installing many temperature sensors on the walls of the battery.

At the NREL both IR photography and liquid crystal thermography are used. The battery pack performance, and thus the performance of an EV or HEV, is affected by its operating temperature and the degree of temperature gradient in the pack. Thermal issues are of more concern in an HEV pack because of higher power and more aggressive charge/discharge profile.

Using finite element analysis software, temperature distributions in a hypothetical module and pack is obtained. Even with reasonable air flow rates, the temperature in the pack can vary significantly; a pack with no air flow can reach unacceptably high temperature levels.

NREL analysis indicated that adding ventilation holes improved the thermal performance of an HEV battery module. IR and LC thermography were used to obtain thermal images of an HEV module and a simulated HEV pack.
Newman et al., in the second part of their work, [37], proposed a model that uses heat generation rates calculated from isothermal discharges of the one cell model presented in Part I to calculate temperature profiles in cell stacks. This allows considering that cells on the outside of the stack operate at a lower temperature than cells on the inside of the stack, due to conductive heat transfer limitations of the system.

In this model, again, the heat is assumed to be transferred only in the direction perpendicular to cell layers. Due to geometric consideration the temperature behavior of the full cell stacks is assumed to be symmetric.

The boundary region denotes the cell case and the electrolyte surrounding the core region. In terms of heat transfer, the boundary region separates the core region from the outside environment and thus imposes an additional barrier to heat dissipation. However, the electrolyte in this region absorbs heat generated in the core region and thus serves as a heat sink.

2.4.3 Summary

This an extensive and detailed literature review based on the modeling of both electrical and thermal aspects of a li-Ion battery cell. The electrical characterization has been proposed from both, fundamental and phenomenological points of view. There is a detailed discussion on Control-oriented models of li-ion batteries for automotive. Two parts have been made of the review of thermal characterization of li-Ion battery, one is single cell thermal model and pack thermal model. The state of art of thermal management system of Li-Ion battery has been reviewed at the end. The analyzations of the state of the art conclude that a more detailed thermal model, is able to capture the temperature dynamic
of a Li-Ion battery cell, is needed to improve the accuracy of models developed for control and optimization. Later in the thesis Chapter 3 presents the modeling approach to implement a model of the thermal dynamics of a li-ion battery cell.
CHAPTER 3

Thermal Dynamics of Battery

3.1 Modeling the Thermal Dynamics of Lithium-ion Batteries

Li-ion batteries have become dominant and their greater specific power and energy content can easily overcome the limitations in meeting the power demands of HEVs and PHEVs typical of Ni-MH batteries. A broader range of temperatures can be with stand by them.

Since the last twenty years, many thermal management approaches were studied, consisting mainly of air-cooling system (ACS) [38], liquid cooling system [39], phase change material (PCM) cooling system [40] and heat pipe cooling system [41]. Simple structure and low cost being the reason, the earliest cooling technique that used for the battery thermal management was ACS. Wu et al. investigated the experimental and numeric results which showed that the heat from the battery pack could not be cooled effectively by natural convection cooling whereas the forced convection cooling attained satisfactory the temperature rises of the battery. It was numerically studied by Park and Jung that the effect of the battery cell arrangement on the thermal performance of the ACS and the parasitic power consumption. A wide battery module with a small cell to cell gap was desirable for the ACS was found out. The consumed power of the ACS was much more than that of the liquid based TMS under large heat load conditions. Even if a better cooling performance of the ACS could be achieved by means of the structure optimized design, the temperature difference in the battery pack was inevitable. The ACS could not effectively control the temperature rises and suppress the temperature difference of the battery. Especially for large capacity and high discharge rate.
The liquid cooling can provide higher cooling efficiency and better thermal uniformity than air-cooling. The TMS based on liquid cooling can easily maintain the battery temperature within a range which is desirable and the variation of temperature from cell to cell is within 2°C [42]. De Vita et al analyzed Transient thermal performance of a lithium-ion battery pack [43] he compared air cooling and liquid cooling strategy. Rao et al. [44] numerically investigated the effect of various control factors, such as the number of channel, flow direction, coolant mass flow rate and ambient temperature on the temperature rise and distribution of the rectangular lithium-ion battery by employing a liquid cooling based TMS on the basis of mini-channel cold plate. In the most recent times, because of the extensive application in solar energy storage fields [45], the PCM based TMS which was used to cool the battery have begun to get increased attention. This simple structure has high latent capacity and consumes no power. Al-Hallaj and Selman leaded the research on a battery module with a PCM based TMS. It was found out that the temperature profile of the cells was substantially more uniform at different rates discharge than those without PCM. In the next study on a scaled-up battery pack, they [46] also presented that the PCM placed between the cells was able to be effectively used as a passive battery TMS without the introduction of moving components. However, the pure PCMs, such as paraffin, are incapable of meeting the demands of rapid heat storage due to the low thermal conductivity. Hence, many studies have been carried out for the betterment of the thermal conductivity by the addition of metal foam, metal fins, or expanded graphite into paraffin [47].

Wilke et al. [48] conducted the nail penetration on a lithium-ion pack and studied how much effective the TMS is with and without phase change composite material. The results made us conclude that as a single cell entered thermal runaway, the TMS with PCM could
prevent the propagation while the TMS without PCM could not. Compared to the TMS without a composite of PCMs and aluminum wire mesh plates, the thermal behavior of the LiFePO4 pack with the TMS was experimentally studied by Azizi and Sadrameli [49]. Our main objective of this thesis is to develop a modeling approach which would be able to characterize the spatial temperature distribution within a Li-ion battery cells is the main objective of this thesis.

3.2 Thermal Modeling Approach and Mathematical Formulation

To design a thermal model of a prismatic Li-Ion battery cell having two different heat absorption materials has to be solved. All the convection problems within the battery cell should be formulated as unsteady problem having non-homogeneous boundary conditions which could vary with respect to both time and temperature. Problem of energy conservation which emerge at the boundaries needs to be introduced to describe the behavior of the medium used to cool the battery. In this section, a review of the basic concept of heat transfer problems will be represented, in relation to the specific problem considered here.

3.2.1 Basic Equations for Heat Transfer

A goal in a heat transfer analysis is the determination of the temperature field in a medium resulting from conditions imposed on its boundaries. Heat is a form of energy in transit because of temperature difference. There are three ways this transfer can occur:

- Conduction of heat throughout a medium due to transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones, as a result of interactions between the particles.
• Convection, which is defined as heat transfer between a surface and a moving fluid.
• Radiation of energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

Unlike convection and conduction, it does not require the presence of an intervening medium when the transfer of energy passing by radiation. This form of transfer relies on the Stefan-Boltzmann law, which for a grey surface is written as:

\[ q_{rad} = \varepsilon \sigma (T_{surface}^4 - T_{surroundings}^4) \text{ W/m}^2 \]  

where \( \sigma \) is the Stefan-Boltzmann constant = 5.67*10^{-8} W/m^2K^4 and \( \varepsilon \) is the surface emissivity. According to [50], radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection. Thus, radiation in forced convection applications, when temperatures are below large values (on the order of 10^2 degree Celsius), is disregarded. Sometimes this way of heat transfer is accounted for in the computation of the convective heat transfer coefficient obtaining thus an overall coefficient for both way of heat diffusion. In this work radiation will always be neglected. The convection heat transfer mode is comprised of two mechanisms: energy transfer due to random molecular motion (diffusion) and macroscopic motion of the fluid (advection). Regardless of the particular nature of the convection heat transfer process the appropriate rate equation is given by the Newton’s law of cooling [50]:

\[ q_{conv} = h (T_{surface} - T_{\infty}) \text{ W/m}^2 \]  

where \( h \) is the convective heat transfer coefficient [W/m^2K] and \( T_{\infty} \) is the average bulk temperature of the fluid. Any study of convection ultimately reduces to a study of means
by which may be determined. The convection heat transfer coefficient is not a property of
the fluid but it is an experimentally determined parameter whose value depends on all the
variables influencing convection such as the surface geometry, the nature of fluid motion,
the properties of the fluid, and the bulk fluid velocity. Convection is known as forced
convection if the fluid is forced to flow over the surface by external agents such as a fan,
pump, or the wind. Contrastingly, convection is called natural (or free) if the fluid motion
is caused by buoyancy forces that are induced by density differences due to the variation
of temperature in the fluid. Plenty of empirical correlations have been derived for external
flows, internal flows, natural convection and boiling or condensation phenomena.

For many of the problems related to the first law of thermodynamic, the energy
conservation law, represents the essential tool which provides the solution to the problem.
Determination of the temperature distribution in a body is done by following a precise
methodology and thus it is necessary to, respectively, define a differential control volume,
identify the relevant energy transfer processes and introduce appropriate rate equations.
The conduction heat transfer fundamentally depends on the heat diffusion equation which
gives the provision of the basic tool for heat conduction analysis. Its general form in
Cartesian coordinates is:

\[
\frac{\partial}{\partial x} (k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (k_z \frac{\partial T}{\partial z}) + q = \rho c_p \frac{\partial T}{\partial y}
\]  

(3.2.3)

where \( k_i \) \((i = x, y, z)\), is the thermal conductivity in different spatial directions, W m-K, \( \rho \)
the density, kg-m\(^3\), \( c_p \) thermal capacity, J kg-K and \( q \) the heat generation rate per unit
volume, W m\(^3\). In the case of isotropic material, which is a common assumption in heat
transfer problems, the thermal conductivity does not vary with respect to the direction chosen and so the equation above can be written as:

\[
\left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{\bar{q}(x,t)}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\] (3.2.4)

Where, \(\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c_p}\) is the thermal diffusivity \(m^2/s\) and represents how fast heat diffuses through a material.

In the technical literature, i.e. [50] or [51], many simplified problems are considered and solved. Particularly relevant to this study is the solution of Equation (3.2.5) for one-dimensional case, specifically when \(\frac{\partial T}{\partial y} = \frac{\partial T}{\partial z} \equiv 0\), the heat diffusion equation reduces to

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\bar{q}(x,t)}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\] (3.2.5)

First, the body will be considered to be in a steady-state situation which means that the temperature does not vary with respect the time but only along the spatial direction. In absence of internal heat generation, the problem can be stated with the well-known Laplace equation

\[
\frac{\partial^2 T}{\partial x^2} = 0
\] (3.2.6)

Solution of Equation (3.2.6) leads one to find that the temperature distribution varies linearly with respect to the space coordinate \(x\) and performing a double integration the analytical solution obtained is: \(T_x = C_1 x + C_2\) where the two variables are obtained imposing the boundary conditions. Considering now the case with presence of heat generation at a rate \(\bar{q}\), the problem becomes
\[
\frac{\partial^2 T}{\partial x^2} + \frac{q}{k} = 0 \quad (3.2.7)
\]

And the corresponding analytical solution is: 
\[
(x) = \frac{q}{2k} C_1 x + C_2
\]

Just as an example, the cartesian solution of a steady-state conduction problem within a plane wall of thickness \( L \) in presence of heat generation and with symmetrical convective boundary conditions results to be:

\[
(x) = T_{\text{surface}} - \frac{q \cdot L^2}{2k} \left(1 - \frac{x^2}{L^2}\right) C_1 x + C_2 \text{where} T_{\text{surface}} = T_\infty + \frac{q L}{h} \quad (3.2.8)
\]

The transient cases are more complex, since now the temperature varies with respect to both space and time. A representative problem of one-dimensional transient heat conduction, without heat generation, has the form:

\[
\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (3.2.9)
\]

These kinds of problems can be solved by the separation of variables method or applying advanced mathematical or numerical methods. However, they are often treated using the lumped parameters method. This simplified approach assumes that the temperature of a solid varies with time but remains uniform throughout the system at any time. As suggested in [51], this assumption provides great simplification in certain classes of heat transfer problems without much sacrifice in terms of accuracy. The temperature distribution with respect to the time can be find performing an energy balance of the solid for the time interval \( dt \). Consider a body of arbitrary shape of mass \( m \), volume \( V \), surface area as, density \( \rho \), and specific heat \( cp \) initially at a uniform temperature \( T_i \). At time \( t = 0 \), the body is placed into a medium at temperature \( T_\infty \), and heat transfer takes place between the body and the medium with a heat transfer coefficient \( h \), as shown in Figure 3.1.
The heat transferred to the body during dt equals the increasing in the energy of the body during the same time step.

\[ h \left( T_\infty - T \right) dt = mc_p dT \] (3.2.10)

Considering \( dT = d(T-T_\infty) \) since \( T_\infty = \) constant, Equation (3.2.10) can be expressed as

\[ \frac{d(T-T_\infty)}{(T-T_\infty)} = \frac{hA}{\rho V C_p} d \] (3.2.11)

Equation (3.2.11) can be easily integrated to obtain the solution to the problem

\[ \frac{T(t)-T_\infty}{T \ (t=0) - T_\infty} = e^{-bt} \text{ where } b = \frac{hA}{\rho V C_p} \] (3.2.12)

The lumped system analysis certainly provides great convenience in heat transfer analysis, but one must wonder when it is appropriate to use it. The criterion used to establish whether the lumped parameters approach is applicable or not consists on the relative comparison of the conduction resistance within the body and the convection resistance at the surface of the body

\[ Bi = \frac{\text{Conduction resistance within the body}}{\text{Convection resistance at the surface}} = \frac{Lc/k}{1/h} = \frac{hLc}{k} \] (3.2.13)
The dimensionless Biot number is the ratio of the internal resistance of a body to heat conduction to its external resistance to heat convection [51]. Therefore, a small Biot number represents small resistance to heat conduction, and thus small temperature gradients within the body. Lumped system analysis assumes a uniform temperature distribution throughout the body, which will be the case only when the thermal resistance of the body to heat conduction is zero. Thus, lumped system analysis would be exact in the limit case of $\text{Bi} = 0$ and approximate or fairly inaccurate when $\text{Bi} > 0$. It is generally accepted that lumped system analysis is applicable when $\text{Bi} < 0.1$ [51]. In a typical case of a li-Ion battery, nevertheless, the Biot number results to be much larger than 0.1 (typical values are between 0.2 and 1.0) and thus the lumped parameters approach is inaccurate.

### 3.3 Assumptions for Battery Modeling

The mathematical assumptions and simplification adopted to write the equations of the battery cell models developed in Chapter 4 will be discussed, from the basic, general, equations presented above. First, as in major heat transfer problem, common assumptions about the different materials that compose the battery are made:

- The cell materials are homogeneous and without bulk motion;
- The cells are isotropic, so that all the properties are independent of the direction;
- The thermal conductivity, $k$, and the other thermo-physical properties are assumed to be constant.

When approaching the heat transfer problem, some simplifying assumptions are used

- Neglection of radiation heat transfer, since the temperatures and their differences are not in this kind of heat transmission interest;
• No concentrated temperature drop (negligible contact resistance) because of perfect contact at the interface of two surfaces;
• The heat generated within the battery to be homogeneously distributed within the cell volume;
• All the flows are considered to present uniform velocity distribution;
• Negligible pressure drops across the channels

3.3.1 Mathematical Formulation of the Simplified System

The problem can be cast into a nonhomogeneous boundary-value problem (BVP) from a mathematical standpoint. For the case of one-dimensional, unsteady heat conduction it is represented by the heat diffusion equation mentioned above (Equation (3.5)):

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\bar{q}(x,t)}{k} = \frac{1}{\alpha} \frac{\partial T}{\partial t}
\]  

(3.3.1)

To solve this equation two boundary conditions and one initial condition must be chosen. In general, there are three kinds of different boundary conditions:

• Specified temperature of an exposed surface (e.g. \( T(x=x_0, t) = \text{const} \));
• Specified heat flux from or to an exposed surface (e.g. \( q = -k\frac{\partial T}{\partial x}(x=x_0, t) \partial x = \text{const} \)).

Note that insulation and symmetry are particular cases of this kind of boundary condition e.g. \( q = -k\frac{\partial T}{\partial x}(x=x_0, t) \partial x = \text{const} \).

• Convection or radiation (e.g. \( -k\frac{\partial T}{\partial x}(x=x_0, t) = h_{\text{convection}} (T(x=x_0, t) - T_\infty) = \text{const} \); \( -k\frac{\partial T}{\partial x}(x=x_0, t) = \varepsilon\sigma (T^4(x=x_0, t) - T_{\text{surroundings}}^4) \).
The initial condition is relative to the temperature at which the medium is at a specific instant of time, $t = 0$ when the analysis of the problem starts.

### 3.4 Summary

This chapter presents the approach of modelling the thermal dynamics of a li-Ion battery and an overview of the basic physical principles which are essential for the implementation of such a model has been given. A detailed discussion regarding the basic principles and physical laws of the energy conservation analysis, fluid flows and heat transfer. The principles described here will prove to be instrumental to solve the under-study program. For any further detail, it is possible to consult the wide literature available for such topics [50, 52]. In Chapter 4 this approach will be used to implement a li-ion thermal modeling methodology.
4.1 Simulations of Battery Model in ANSYS Fluent

In order to conduct numerical heat transfer analysis using ANSYS FLUENT software there should be mathematical model which shows the physics of the problem, governing equations, input variables and the relationship through these parameters. It concerns with the initial and the boundary conditions and its valid range of variation with the governing equations. Moreover, this model is determined to achieve the objectives for the problem by assigning the constraints and defining the related methodology. The calculated heat generation rate is to be the only heat source and injected through the each surface of the cell throughout the battery positive tabs (tab-p) are the source of temperature in the cell zones. The boundary conditions around the cell and positive/negative terminals which are connected to battery are all defined under free convection as shown in Figure 4.2 and CAD model as shown in Figure 4.1.

For this, heat transfer problem a free convection is introduced on all surfaces including the model with gap and without gap for insulation and PCM which interface with the forced convection where contact resistance is \( R_p = 0.001022 \, \Omega \) (ohms) with variable current and forced convection temperature. For the generation of heat, li-ion cell is the key factor. Some studies refer to an isotropic thermal conductivity 0.27 W/m K [53] for the cell material. In this simulation study, the PCM around the terminal surface of the cell is selected in the boundary conditions due to its orthotropic behavior of the cell. It means that the planar (or surface) thermal conductivity of the cell is assumed to be 20 W/m K, and the direction is
considered as a normal to the surface of the cell. Specific heat value for the cell is 871 J/kg k. As stated above, the heat generation rate $Q = 4.218 \times 10^{-7}$ K m$^{-3}$ for 5A (ampere) of the cell is uniform for a common specific current and will be variable with respect to current; which becomes 4.45 W for each cell [54].

In order to determine the effectiveness of the battery pack without material the battery pack was simulated with no cooling system at different convective temperatures. In case of no material added, ten cells are connected in series through copper plates are used. The current is passing through the tabs all the way to center of the cell. The convective temperature is passing through each face of the cell throughout the battery as shown below.

![Battery Pack Model](image)

Figure 4.1: 5s2p battery pack model

The main factor due to which heat generation takes place is internal resistance of the battery. Convection temperature, heat transfer coefficient temperature and heat generation rate are the factors to observe the thermal effects as shown in Figure 4.2. Inlet and outlet
temperature has kept constant throughout the battery. In the present study, the heat generation rate due to contact resistance is considered and are listed below:

Table 4.1: Heat generation rates due to contact resistance for Li-ion cells under thermal convection conditions

<table>
<thead>
<tr>
<th>S. No</th>
<th>Heat generation rate (W/m³)</th>
<th>Current (Ampere)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.218e-7</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>9.491e-5</td>
<td>75</td>
</tr>
<tr>
<td>3</td>
<td>4.319e-4</td>
<td>160</td>
</tr>
</tbody>
</table>

Figure 4.2: 5x2p battery pack model under boundary condition
4.1.1 Temperature Graphs for 5s2p with Air

At 5 A, cell 3 to cell 10 of the battery pack reaches to 310 K in 50 sec and becomes uniform under flow time for 60 sec.

Figure 4.3: 5s2p battery pack, cell-8 for 60 sec at 310 K

At 5 A, each cell of the battery pack reaches to 310 K in 200 sec and becomes uniform (steady state) under the flow time to and after 1000 sec.

Figure 4.4: 5s2p battery pack, cell-10 for 1000 sec at 310 K
At 5 A, cell 4, cell 6, cell 8 shows the same initial rise in temperature (390 K) and the rest of the cells have approximately same initial rise of the battery pack and keeps on rising until 60 sec.

![Graph showing temperature rise over time](image)

Figure 4.5: 5s2p battery pack, cell-8 for 60 sec at 310 K

At 5 A, cell 9 and cell 10 shows same initial temperature rise in the temperature (392.5 K) of the battery pack reaches and keeps on rising until 60 sec.
At 5 A, cell 4, cell 6, cell 8 shows the initial rise in temperature (397 K) and the rest of the cells does not show major difference and becomes uniform in 300 sec.

Figure 4.6: 5s2p battery pack, cell-10 for 60 sec at 400 K

Figure 4.7: 5s2p battery pack, cell-8 for 1000 sec at 400 K
At 75 A, cell 4, cell 6, cell 8 shows the initial rise in temperature (309 K) and the rest of the cells does not show major rise in temperature and becomes uniform at 50 sec under flow time of 60 sec.

Figure 4.8: 5s2p battery pack, cell-6 for 60 sec at 310 K

At 75 A, cell 9 and cell 10 shows same initial temperature rise in the temperature (309 K) of the battery pack reaches and keeps on rising until 40 sec. When it is under flow time for 1000 sec; no major effect in temperature and reaches to 310 K in 300 sec for each cell.

Figure 4.9: 5s2p battery pack, cell-10 for 60 sec at 310 K
At 75 A, cell 4, cell 6, cell 8 shows the initial rise in temperature (389 K) and the rest of the cells does not show major rise in temperature and becomes uniform at 50 sec under flow time of 60 sec.

![Graph showing temperature rise over time](image)

Figure 4.10: 5s2p battery pack, cell-8for 60 sec at 400 K

At 75 A, cell 4, cell 6, cell 8 shows the initial rise in temperature (397 K) and becomes uniform in 300 sec and cell 3, cell 5, cell 7 shows the initial rise in temperature (397 K) and becomes uniform in 500 sec. cell 9 and cell 10 have initial rise at 398 K and becomes stable in 350 sec.
At 160 A, cell 4, cell 6, cell 8 shows the initial rise in temperature (309 K) and the rest of the cells does not show major rise in temperature and becomes uniform at 50 sec under flow time of 60 sec.

Figure 4.11: 5s2p battery pack, cell-6 for 1000 sec at 400 K

Figure 4.12: 5s2p battery pack, cell-8 for 60 sec at 310 K
At 160 A, cell 9 and cell 10 shows same initial temperature rise in the temperature (309 K) of the battery pack and reaches at 310 K in 40 sec. When it is simulated for 1000 sec there is no effective rise in temperature. At 160 A, when it is simulated for 1000 sec it shows the same graphs as 75 A for 400 K. At 160 A, when it is simulated for 1000 sec it shows the same graphs as 75 A for 400 K.

![Figure 4.13: 5s2p battery pack, cell-10 for 60 sec at 310 K](image)

### 4.1.2 Temperature Graphs for 5s2p with Insulation

At 5 A, initial temperature at cell 8 308.5 K and rest of the cells have similar initial rise with no major difference does reaches up to 310 K. insulation material prevents the initial rise in temperature. Insulation-1 and 4, insulation-2 and 3, in battery packs holds same initial temperature. There is no major rise in temperature under the flow time for 1000 sec; insulation-2 and 3 has same temperature rise but it does not absorb the temperature up to 310 K
Figure 4.14: 5s2p battery pack cell-8 for 60 sec at 310 K

Figure 4.15: 5s2p battery pack, insulation-3 for 60 sec at 310 K
Figure 4.16: 5s2p battery pack, insulation-4 for 1000 sec at 310 K

At 5 A, initial temperature at cell 8 is 386 K and cell 5 and cell 6 have initial rise at 382 K except cell-1 and cell-2 which has 397 K, becomes uniform but in rest of the cells temperature keeps on rising up to 60 sec. Insulation-2 and 3, in battery packs holds same initial temperature keeps on rising under flow of 60 sec.

Under the flow time for 1000 sec the temperature has initial rise from 392.5 K for 200 sec but it will not absorbs the temperature up to 400 K and becomes uniform at 395 K.
Figure 4.17: 5s2p battery pack, cell-8 for 60 sec at 400 K

Figure 4.18: 5s2p battery pack, cell-10 for 60 sec at 400 K
Figure 4.19: 5s2p battery pack, insulation-2 for 60 sec at 400 K

Figure 4.20: 5s2p battery pack, cell-8 for 1000 sec at 400 K
At 75 A, when the flow time for 60 sec the results are similar to 5 A with a difference of 1 K and temperature keeps on rising up to 60 sec for insulation and no major difference when flow time under 1000 sec at 4000 K. It does not make any big difference with the 160 A: initial temperature will be same, uniformity (stable) in temperature may vary.

4.1.3 Temperature Graphs for 5s2p with PCM

At 5 A, cell-8, cell-10 have initial temperature rise from 308.5 and rest of the cells have similar rise and keeps on increasing. PCM-4, 6, 8 shows the similar melting for 60 sec whereas, PCM-1 becomes uniform after 20 sec under the flow time for 60 sec. cell-10 have rising for 200 sec and becomes uniform.
Figure 4.22: 5s2p battery pack, cell-8 for 60 sec at 310 K

Figure 4.23: 5s2p battery pack, cell-10 for 60 sec at 310 K
Figure 4.24: 5s2p battery pack, PCM-6 for 60 sec at 310 K

Figure 4.25: 5s2p battery pack, PCM-1 for 60 sec at 310 K
Figure 4.26: 5s2p battery pack, cell-10 for 1000 sec at 310 K

Figure 4.27: 5s2p battery pack, PCM-8 for 1000 sec at 400 K

At 5 A, cell-8, cell-10 have initial temperature rise from 385 K and 387 K and it shows the steady state condition under the flow time for 60 sec. PCM-8 have melting from 350 K for
60 sec and keeps on melting, whereas, PCM-8 has melting up to 200 sec and after 600 sec the rest of the temperature went to the ambient.

Figure 4.28: 5s2p battery pack, cell-10 for 60 sec at 400 K

Figure 4.29: 5s2p battery pack, cell-10 for 60 sec at 400 K
Figure 4.30: 5s2p battery pack, PCM-8 for 60 sec at 400 K

Figure 4.31: 5s2p battery pack, cell-8 for 1000 sec at 400 K
Figure 4.32: 5s2p battery pack, PCM-8 for 1000 sec at 400 K

At 75 A, PCM-8 has melting up to 200 sec and after 350 sec the rest of the temperature went to the ambient. Similar graphs show for the 160 A under the flow time for 60 sec and 1000 sec.

Figure 4.33: 5s2p battery pack, PCM-8 for 1000 sec at 400 K
**Table 4.2: Phase change material for 5A in 1000 sec at 400 K**

<table>
<thead>
<tr>
<th>PCM no.</th>
<th>Initial temperature (k)</th>
<th>Melting time (sec)</th>
<th>Melting temperature (k)</th>
<th>Final temperature (k)</th>
<th>Time to uniform (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>392.5</td>
<td>200</td>
<td>397.5</td>
<td>398.5</td>
<td>400</td>
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<td>2</td>
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<tr>
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<td>200</td>
<td>397.5</td>
<td>398.5</td>
<td>400</td>
</tr>
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<td>398.5</td>
<td>400</td>
</tr>
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<td>200</td>
<td>396</td>
<td>397.5</td>
<td>600</td>
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<tr>
<td>10</td>
<td>395</td>
<td>200</td>
<td>399.5</td>
<td>400</td>
<td>350</td>
</tr>
</tbody>
</table>

**Table 4.3: Insulation material for 5A in 1000 sec at 400 K**

<table>
<thead>
<tr>
<th>Insulation no.</th>
<th>Initial temperature (k)</th>
<th>Melting time (sec)</th>
<th>Melting temperature (k)</th>
<th>Final temperature (k)</th>
<th>Time to uniform (sec)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>200</td>
<td>370</td>
<td>375</td>
<td>650</td>
</tr>
<tr>
<td>2</td>
<td>340</td>
<td>200</td>
<td>365</td>
<td>370</td>
<td>550</td>
</tr>
<tr>
<td>3</td>
<td>340</td>
<td>200</td>
<td>365</td>
<td>370</td>
<td>550</td>
</tr>
<tr>
<td>4</td>
<td>352.5</td>
<td>200</td>
<td>370</td>
<td>375</td>
<td>650</td>
</tr>
</tbody>
</table>
4.1.4 Contours for Temperature Distribution with Air

As the heat generated in the cell and the temperature is passing through each surface of the cell which in turns increases the temperature in cell and projected area of temperature is as shown in following figures.

Figure 4.34: Area of 5s2p battery pack in X direction

The temperature is higher at rear face of the cell and lower at the front face of the cell. The outlet of the battery shows maximum temperature distribution as compared to inlet of the battery.
Figure 4.35: Area of 5s2p battery pack in Y direction

Figure 4.36: Area of cell-8 in 5s2p battery pack in X-direction
4.1.5 Contours for Temperature Distribution with Insulation

Figure 4.37: Area of cell-8 in 5s2p battery pack in Y-direction

Figure 4.38: Contours of 5s2p battery pack Front face
Figure 4.39: Contours of 5s2p battery pack rear face

Figure 4.40: Area of 5s2p battery pack in X-direction
Figure 4.41: Area of 5s2p battery pack in Y-direction

Figure 4.42: Area of Insulation-2 in 5s2p battery pack in X-direction
Figure 4.43: Area of Insulation-2 in 5x2p battery pack in Y-direction

Figure 4.44: Area of Insulation-1 in 5x2p battery pack in X-direction
The area projected by the maximum temperature with insulation material is shown in the above section in $x$ and $y$ direction. The area projected in $x$ direction is less as compared to $y$ direction.

4.1.6 Contours for Temperature Distribution with PCM

The battery pack is employed with ten pcm, each unit (two cells) has two pcm on its faces. The current is passing through the battery at a constant temperature throughout the battery. The tabs are also the source of current which in turn rises the temperature of the cells. The Figure 4.46 and Figure 4.47 shows the front and rear face of the battery pack which has minimum temperature at the front and maximum temperature at the rear face of the battery.
The average area covered by the battery pack in $x$ direction is $0.0128024 \, \text{m}^2$ and in $y$ direction is $0.018912 \, \text{m}^2$ as shown in figure 4.48 and Figure 4.49.
Figure 4.48: Area of 5s2p battery pack in X-direction

Figure 4.49: Area of 5s2p battery pack in Y-direction
It is possible to observe the results for each of the cell, so we have cell 8 from the battery pack and its area projected by the maximum temperature in x direction is 0.001065 m² and in y direction is 0.001575 m² as shown in figure 4.50 and figure 4.51

Figure 4.50: Area of cell-8 in 5s2p battery pack in X-direction
Figure 4.51: Area of cell-8 in 5s2p battery pack in Y-direction

Figure 4.52: Area of PCM-6 in 5s2p battery pack in X-direction
It is also possible to observe the results for each pcm of the cell, so we have pcm 6 from the battery pack and its area projected by the maximum temperature in $x$ direction is 0.00042286 $m^2$ as shown in Figure 4.53

![Image](image.png)

**Figure 4.53: Area of PCM-6 in 5s2p battery pack in Y-direction**

The observed results for pcm 8 from the battery pack and its area projected by the maximum temperature in $x$ direction is 0.0010322 $m^2$ and in $y$ direction is 0.0004105 $m^2$ as shown in Figure 4.54 and Figure 4.55. The center of the pcm shows the maximum distributed temperature and the boundary of the pcm shows the minimum temperature.
Figure 4.54: Area of PCM-8 in 5s2p battery pack in X-direction

Figure 4.55: Area of PCM-8 in 5s2p battery pack in Y-direction
Comparison in PCM-2 and superwool-2 in battery pack which shows that PCM with high thermal conductivity have approximate same projected area as superwool material.

Figure 4.56: Area of Insulation-2 in 5s2p battery pack in Y-direction

Figure 4.57: Area of PCM-2 in 5s2p battery pack in Y-direction
5. Conclusions and Future Work

5.1 Conclusions

In this thesis, a method for li-ion battery management system by integrating PCM was studied experimentally to determine the effectiveness of the thermal management of heat dissipation in simulation model. In battery pack, for PCM, cell and material (PCM) both gradually increases the surface temperature of the cell but the initial rise in the cell with PCM has reduced as compare with insulation material. As the heat generation rate changes, there is no major difference in the temperature curves; due to its small contact resistance. PCM with high thermal conductivity (2.23 w/m k) along with a thickness of 0.32 mm have low initial rise and reaches to desired set temperature as compare to superwool material having thermal conductivity of (0.5 w/m k) along with a thickness of 3.2 mm. PCM can control the battery temperature better and effective than the insulation, they suffer due to their low thermal conductivity. The temperature elevation curve can be divided into two parts: the temperature rises rapidly if it is below or above the phase change temperature and temperature rises slowly if it falls within phase change temperature. Superwool does not absorb more heat and melt for a longer time but it may resist the rise in temperature and can use as a safety purpose as it does not show phase change in material. The average temperature area projected by 5s2p battery pack with PCM is approximately similar, but the area projected by the PCM 0.4% less than superwool material. The temperature rise rate of pcm is higher at the initial stage of heat charge but lower in phase change process. This pcm has high thermal conductivity and can also resist rise in temperature of PCM which shows great potential for li-ion battery pack.
5.2 Future Works

1) In future works, 5s2p battery pack can be developed with consideration of SOC, SOH, and remaining useful life (RUL). The model accuracy can be still improved by incorporating the influence of various parameters like C-rate, temperature, changes in DOD, and impedance etc.

2) To improve the thermal conductivity of PCM, some graphite property can be added to use as composite PCM and would be liable to work on practical experiments.

3) We can focus on integrating and implementing the different thickness of pcm with different thermal conductivity in battery pack. PCM with solid, solid-liquid, molten material can also be used as experiment for further research.

4) A large pcm thickness around the surface of the cell which in turn could show larger depth of the curvature for better cooling in battery pack.

5) It can achieve maximum optimal thermal performance when battery pack simulated under isolated system with different electrical parameters.
REFERENCES


[16] Battery Data Set NASA Ames Prognostic Data Repository


[38] Fan L, Khodadadi JM, Pesaran AA. A parametric study on thermal management of an air-cooled lithium-ion battery module for plug-in hybrid electric vehicles. J Power Sources 2013; 238:301–12.


[53] Vedat S. Arpaci, Conduction heat transfer: Addison-Wesley.

[54] Battery Pack (NAVY STTR) pdf”.