THERMAL DESIGN AND SIMULATION OF COOLING SYSTEM FOR PERFORMANCE IMPROVEMENT OF LI-ION BATTERIES FOR VEHICLES

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NOVEMBER 2019

THERMAL DESIGN AND SIMULATION OF COOLING SYSTEM FOR PERFORMANCE IMPROVEMENT OF LI-ION BATTERIES FOR VEHICLES

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

Thermal Design and Simulation of Cooling System for Performance Improvement of Li-Ion Batteries for Vehicles

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In today's world, the energy demand has been increasing inevitably due to growing population and in this case use of too many cars are one of the main energy consumers in our planet. Since fossil fuels are finite energy resources and have CO_2 emissions, new technologies have been studied and used for transportation. Thus, automobile manufacturers work on electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). These technologies are more efficient than traditional internal-combustion engines and are environmentally friendly. In this study, performance of electrical vehicles is examined, thermal management system of batteries is investigated, and thermal issues that affect the battery performance are studied. The aim and scope of the thesis are monitoring the effect of temperature change on battery performance and simulating alternative cooling methodologies and proposing a feasible cooling system design. Different cooling fluids, cooling geometries and heat transfer methods are examined, and the most suitable ones has been simulated and compared with different discharge rates. In this context, aluminum battery module and assembled channel types have been compared numerically. Validation of the numerical model is performed by testing a single battery under 3C discharge rate, producing heat generation as function of time and comparing with

numerical model. As a result, aluminum block used with vertical channel type design is found to be more effective design.

Keywords: Liquid Cooling, Channel Type Cooling, BTMS, Electrical Vehicles

ÖZ

Araçlardaki Li-Ion Pillerin Soğutma Performaslarının İncelenmesi, Tasarım ve Test Ederek Değerlendirilmesi

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Kasım 2019, 88 sayfa

Günümüz dünyasında, artan nüfus nedeniyle enerji talebi kaçınılmaz şekilde artmaktadır ve bu durumda artan araba kullanımı gezegenimizdeki ana enerji tüketicilerinden biridir. Fosil yakıtlar, sonlu enerji kaynakları ve CO_2 emisyonları sahip olduğundan, yeni teknolojiler araştırılmış ve ulaşım için kullanılmıştır. Böylece otomobil üreticileri elektrikli araçlar (EV), hibrit elektrikli araçlar (HEV) ve takmalı hibrit elektrikli araçlar (PHEV) üzerinde çalışmaktadır. Bu teknolojiler geleneksel içten yanmalı motorlardan daha verimli ve çevrecidir. Bu çalışmada, elektrikli araçların performansı, bataryaların ısıl yönetim sistemi ve batarya performansını etkileyen termal konular incelenmiştir. Tezin amacı ve kapsamı, sıcaklık değişiminin pil performansı üzerindeki etkisini izlemek ve alternatif soğutma metodolojilerini simüle etmek ile beraber mantıklı bir soğutma sistemi tasarımı önermektir. Farklı soğutma akışkanları, soğutma geometrileri ve ısı transfer yöntemleri incelenmiş ve en uygun olanları simüle edilmiş ve karşılaştırılmıştır. Bu bağlamda alüminyum bateri modülü ve montajlı kanal tipleri sayısal olarak karşılaştırılmıştır. Sayısal modelin

validasyonu, 3C boşalma hızı altında tek bir akünün test edilmesi, zamanın fonksiyonu olarak ısı üretimi ve sayısal model ile karşılaştırılması ile gerçekleştirilmiştir. Sonuç olarak, dikey kanal tipi tasarımında kullanılan alüminyum bloğun daha etkili tasarım olduğu tespit edilmiştir.

Anahtar Kelimeler: Sıvı Bateri Soğutma, Kanal Tipi Sıvı Bateri Soğutma, Li-İon Bateri.

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CHAPTER 1

INTRODUCTION AND FUNDAMENTALS

1.1. General Information

In today's world, the energy demand has been increasing inevitably due to growing population and improved high standard of life quality. Well-developed countries that have high potent manufacturing-based industry and service sector offers an attractive living space for people. In this case, an intensive industry, domestic usage and the use of too many cars are the main energy consumers in our planet. There is an example shown below defines the rate of change energy consumption yearly over the last decades in terms of MTOE (a kind of energy unit equals to 10^6 kcal for million tons of oil equivalent)

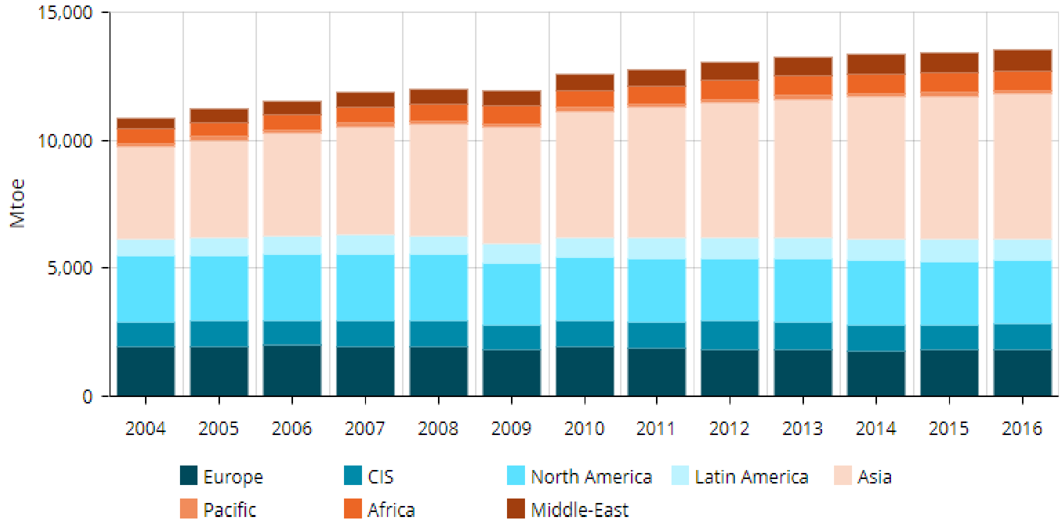


Figure 1 Global energy statistical distribution [1].

There are many energy resources in world, and they can be developed with advance R&D facilities. However, most of the resources are based on finite energy sources, fossil fuels. As seen Figure 2, 80 percent of energy consumed includes fossil fuel derivatives; coal, natural gas and oil. However, there is a crystal-clear fact that the greatest danger the planet faces occurs due to usage of fossil fuels.

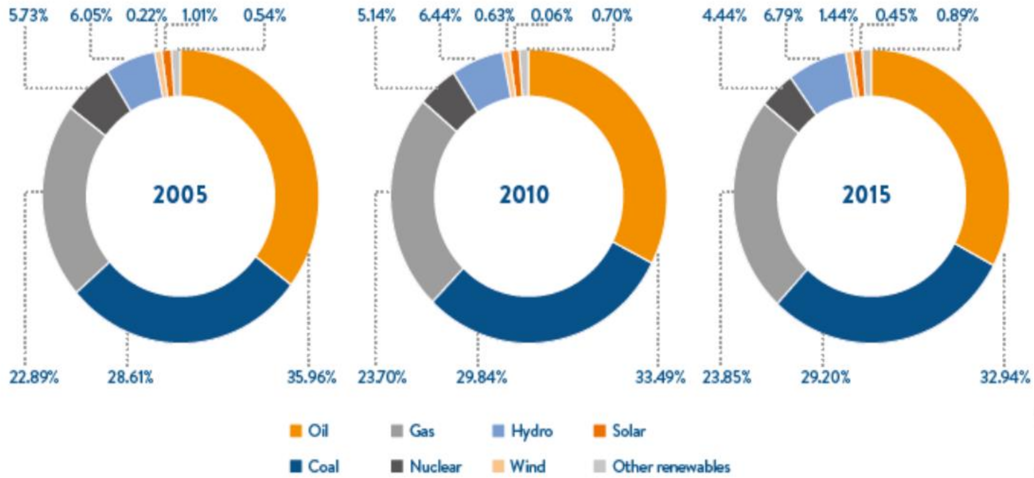


Figure 2 Energy resources and their consumptions[2].

Burning of fossil fuels emit CO_2 excessively compared to others (methane, nitrous oxide and fluorinated gases). Mostly CO_2 triggers to heat Earth atmosphere's that is called as greenhouse effect, discovered by Joseph Fournier in 1827. The greenhouse effect causes some vital problems on the ecology directly and that doesn't only carry a high-risk for today, it also carries a risk for living things for the next years.

In modern life, the consumption of energy sources, environmental pollution and the global warming are the most debated issues that revived in relevant international organizations and there are many social studies to raise awareness for members of consumer society. Increased energy demand and depleting energy sources cause to increase unit price in the energy sources. Therefore, the importance of renewable energy sources will increase while increase of unit price of energy source.

Today, one of the most damaging energy sources, petroleum (oil) products, has been taking a place in our daily life as an indispensable need. Those are being consumed by many sectors; services, household, industry and transportation. However, according to BP energy Outlook 2016, two-third of global oil has been consumed by transportation sector. This statistic shows us that transportation sector is the one of the main reasons of global warming which is a big problem world is struggling. Although there are many technological advancements to reduce CO_2 emissions during fuel consumption for automobiles, it remains an inadequate solution against increasing demand and price. Therefore, automobile manufacturers made an investment to support R&D works to find out alternative energy – based on electricity; electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). All of them are more efficient than traditional internal-combustion engines and they are environmentally friendly tools for transportation.

Even tough development and first try of electrical vehicles based on a hundred years, electrical vehicles take firm steps forward in the past 15 years. For now, free competition sector has many alternatives. Also, sales figures show us that usage of electrical vehicles will increase exponentially.

1.1.1 Destination

For the environmentally friendly electrical vehicles, some of the real concerns are how to store enough energy to support long distance kilometers, how often it needs charging and how long is its battery life expectancy?

From those concerns; battery life expectancy and the performance of the battery are the most important variables compared to others. Because of the fact that battery includes many chemical properties and derivatives, its characteristic features show differences. For the background of the battery usage, there are various kinds used in different areas, including smartphones and laptop to household appliances. In Table 1. various batteries are listed, and their performance, life expectancy and charge rates are shown.

Table 1 Properties of different materials that are used as electric vehicle batteries adapted from [3]

Type	Specific energy (W h kg^{-1})	Specific power (kW kg^{-1})	Nominal cell voltage (V)	Life cycles[1]	Charge time (h)	Self-discharge rate[2] (%)
Lead-acid	25–40	150–250	2	200–700	8	5
Nickel-	45–80	200	1.2	500–	1	20

cadmium				2000		
Nickel-metal hydride	60–120	200	1.2	500–1000	1	30
Nickel-iron	50	100	1.2	2000	/	20–40
Nickel-zinc	70	150	1.7	300	/	20
Sodium-sulphur	100	150–200	2	~1000[3]	8	Quite low
Sodium metal chloride	100	150	2	> 1000[4]	8	/
Li-ion	110–180	300	3.6	> 1000	2–3	10
Li-polymer	100–130	300	3.6	300–500	2–4	10

1 Up to 80% capacity.

2 Loss per month.

3 ~1000 means no more than 1000.

As seen from the Table 2, Li-ion batteries are the most suitable ones compared the other options considering performance and life cycle aspects. Li-ion batteries are the core points of this study. Although, Li-ion batteries are the best choice, some disadvantages make them unreliable power sources. Those disadvantages are; low usable life, expensive renewal costs and temperature fails.

Table 2 Characteristic properties of positive electrodes adapted from [3]

Positive Electrode	$LiCoO_2$	$LiNiO_2$	$Li(Ni_{0.8}Co_{0.15}Al_{0.05})O_2$	$Li(Ni_{1-x-y}Mn_xCo_y)O_2$	$LiMn_2O_4$	$LiFePO_4$
Abbr.	LCO	LNO	NCA	NMC	LMO	LFP
Cell votage (V)	3.7–3.9	3.6	3.65	3.8–4.0	4.0	3.3
Specific energy	III	III	IV	IV	II	II
Power	II	II	III	II	III	III
Safety	I	II	II	II	III	IV
Lifespan	II	II	III	II	II	III
Cost	I	III	II	II	III	III

Excellent: IV; Good: III; Moderate: II; Bad: I.

1.2. Motivation and Aim of the study

In this study, thermal issues that affect the battery performance is addressed under the title of battery thermal management systems. The aim and scope of the thesis is monitoring the effect of temperature change on batteries, simulating alternative cooling methodologies and proposing a sensible cooling system design. Methods are changing cooling fluids, cooling geometry and trying different active or passive heat transfer enhancements.

1.3. Fundamentals of Li-ion Batteries

1.3.1. Li-ion Battery and Battery Pack

In this section, characteristic information and working principles of Li-ion Batteries are discussed. For the first sub-section, battery framework and specific information are given. Next, working principle of Li-ion batteries are introduced in the second sub-section.

1.3.1.1. Characteristic and Specific feature of Li-ion Battery

A li-ion battery consists of 6 main parts; positive and negative electrodes, electrolyte, separator, current collector and cover [4].

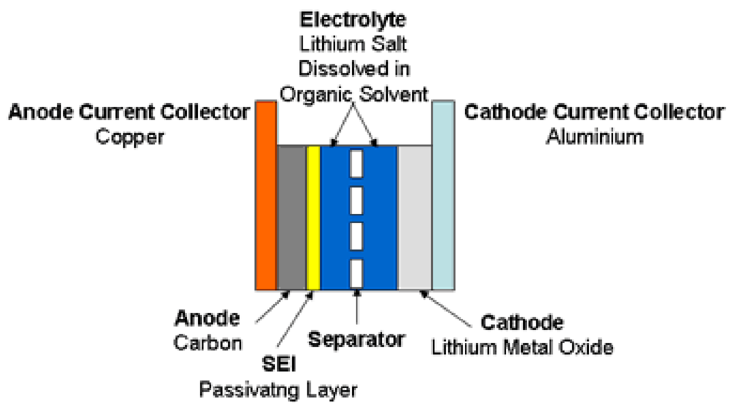


Figure 3 The physical structure of lithium-ion battery[5]

Electrodes are the main functions that defines performance capacity and energy density of the battery. Due to highly-effected capability over the performance of Li-ion batteries, positive electrode became mostly researched topic for last years. Generally, R&D stages of the positive electrode has focused to use different chemical compound to improve its performance. Mostly researched compounds can be divided into 3 main varieties as the layered structure, the spinel structure and the olivine structure (Dahlin GR, Strom KE. Lithium batteries: research, technology and applications; 2010). In industry, $LiCoO_2$ (LCO) and $LiNiO_2$ (LNO) are used as layered structures. $LiMn_2O_4$ (LMO) is used as term spinel and lastly, transition metal phosphates containing lithium (e.g. $LiFePO_4$ (LFP) and $LiMnPO_4$ (LMP) are the most olivine structure kind. $LiCoO_2$ (LCO) is the most preferable choice in automotive industry. Their performance, cost, safety and lifespan over tower to each other, their compression can be reached from the Table 2 [6,7].

$LiCoO_2$ is the most preferable option among those materials in aspects of high capacity and maturity process. On the other hand, $LiFePO_4$ is the most resistant option. On the other hand, there is no many options to choose material as negative electrodes. Generally, negative electrodes made of carbon compounds, such as coke and graphite. The most commercially used one of negative electrode is graphite-based carbon. There are many researches to improve negative electrodes, even though there are limited options on it. Maybe $Li_4Ti_5O_{12}$ and silicon might be preferable option as negative electrode in long term.

Electrolytes are non-aqueous materials of battery. Electrolytes provide to flow current in in between separator and electrodes. For example, such as ethylene carbonate (EC), propylene carbonate (PC), diethyl carbonate (DEC) or ethyl methyl carbonate (EMC) are the most common options in industry.

The separator is device that avoid internal short circuit in between positive and negative electrodes. The separator is electrical insulator, provide to block and crossing over under normal conditions. The separator also can stop current flow in case of exposed high temperature density.

The current collector is consisting of Cuprum and Aluminum. Aluminum face symbolize the positive side, Cuprum side symbolize the negative side. Those materials, Aluminum or Steel, gain advantages in aspects of mechanically and thermodynamically resistant. The duty of current collector is that collect current that produced in battery and creating signal to adjust amplitude of current to control mechanism.

1.3.1.2 Types of Li-ion Batteries

Two different shape and configuration of Li-ion cells are used in EVs. Their main structure can classify as cylindrical and prismatic. In figure below, it can be seen that their sub structures.

Although their some specific features over tower to each other, prismatic cells generally use when needing to keep spaces efficiently in EVs. Cylindrical cells are very economical, easy to implement and more commercial in industry. And, cylindrical batteries can withstand high internal pressure due to its geometry without any deformation, internal surface pressure can spread same almost all internal area.

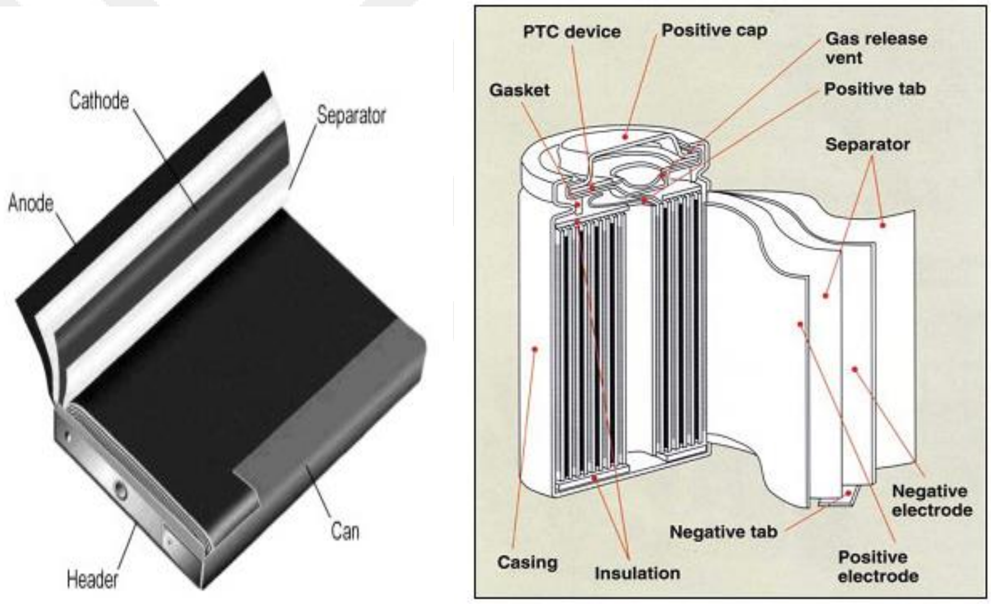


Figure 4 Types of batteries and their structures [7]

1.3.1.3. Working Principle of Li-Ion Batteries

The operations of a battery can be separated into two main phases basically; charge and discharge operations.

During the charge phase, li-ions moves from the positive electrode through electrolyte and separator to the negative electrode. In order to keep electrical equilibrium, same number of electrons with ions must be released from side of positive electrode. Then, those electrons are collected in positive side of current collector and moves with external circuit that initiates from negative electrode.

During the discharge phase, electro chemical process is inversed in direction regarding charging phase. The detailed chemical formulation and definition is given in the next section. In figure below, representation of charging and discharging operation is shown.

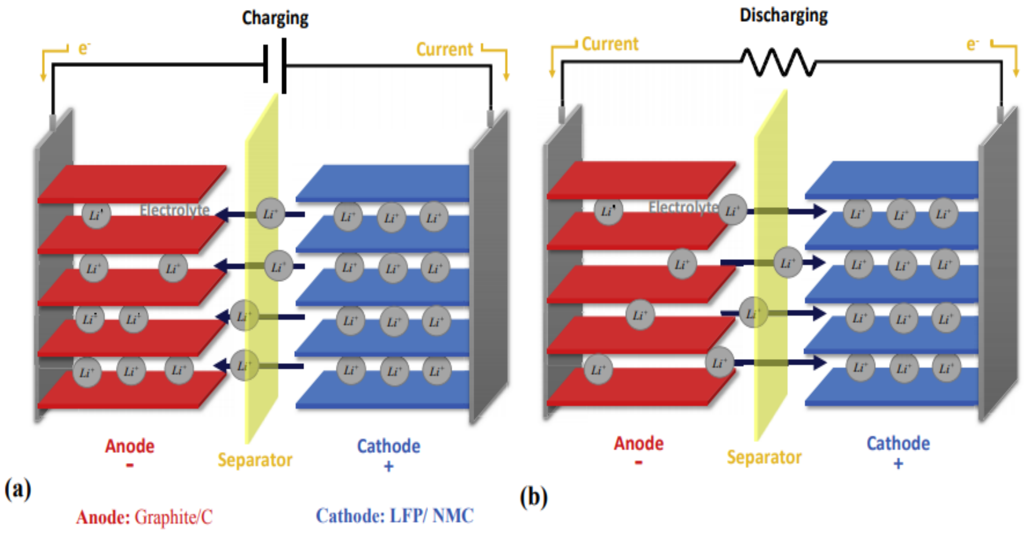


Figure 5 Operation process illustration of charge and discharge shown[8]

1.4. Thermal Characteristics of Batteries

In this section, thermal issues of Li-Ion batteries, operational processes and theoretical background are given respectively.

1.4.1. Thermal Issues of Li-ion Batteries

The most important assessable characteristic feature of li-ion battery is the performance. Performance is decisive and competitive key factor to choose batteries that are used in EVs. From this perspective, main criteria's that affect the performance of Li-ion batteries can be directly related to operating voltage and temperature. Working with limited voltage range and controllable temperature can avoid damage to the battery.

Operating voltage and temperature do not only affect the performance of batteries, but they also cause damage and decrease calendar life.
Exposing to over voltage can cause capacity loss of batteries and breaking down of electrodes Excessive voltage reflects excessive current in battery. Excessive current

causes the Lithium-ions to accumulate unusually than electrochemical intercalation. In normal charging or discharging processes, electrons and lithium-ions intercalate electrochemical equilibrium in both current collector and current separator to the positive or negative electrodes. As a result of excessive flow of current, the lithium-ions will create residue on the surface of anode as metallic Lithium. This formation restricts circulation of free lithium-ion, so it causes capacity loss of battery.
Another problem that comes with over voltage is breakdown of the electrode materials which mostly occurs in the anode of the battery. In anode, copper current breaks down. As a result of this effect, copper ions create precipitate and deposit in the deep of battery. This formation destroys charging and discharging rate in long term, so calendar life of battery becomes restricted due to this reason. Also, it can cause the most dangerous problem that might be faced in a battery, which is short circuiting. Short circuit uncovers irreversible safety concerns which are still valid for many EVs customers.

Temperature effect on the battery can be classified in two main parts as excess heat and lack of heat. In both case, there will be some problems that effect both performance and calendar life of battery.

Temperature and electrochemical reactions interact with each other directly. If environmental temperature decrease, then reaction rate will reduce and carried current will also reduce related with reaction rate. As mentioned above, this can be associated with capacity loss. It even causes formation of lithium plate on the surface of the anode as a result of reduced power.

Rapidly increase of temperature, increases the reaction rate and power output. This also increases the heat generation. If generated heat is not evacuated than battery temperature will be unpreventably higher, and it may create thermal runaway. There is a few stages of thermal runaway, each of them harms the battery in different rates. At the first stage, the solid electrolyte interphase (SEI) layer might be damaged around 80° C. As a result of breakdown of SEI layer, electrolyte may contact anode. At the second stage, hydro carbon gases in organic solvent may be freed to move inside the battery. This gas causes increase in internal pressure of battery around 110 °C. At third stage, separator will be melted, and short circuit will be unpreventable around 135°C. At the final stage, a metal-oxide cathode by breaker down at 200 ºC, then oxygen will be released, it opens the way of formation of burning reaction with hydrogen (Electropaedia, 2014).

In addition, if the accumulated heat inside the battery doesn't evacuate properly, formation of uneven temperature distribution would be inevitable problem to affect both performance and calendar life of the battery. This problem is called as temperature maldistribution. Uneven heat convection coefficient of battery, from surface to inner base, may cause permanent heat source inside the battery. This is one of the most important reason for temperature maldistribution. Therefore, the preferred geometry of battery carries high importance for the design of battery pack. The cylindrical type of battery get superiority over the prismatic cell in the aspect of temperature distribution in battery.

Heat generation inside the cell is not uniform and temperature inside the battery is not identical at different locations. Chemical reaction cannot be restricted during the reaction for both charging and discharging. For example, during the charging of the battery, $LiCoO_2$ positive electrode is exposed 4 times greater heat as much as any point inside the cell. Thermal study on single electrodes in lithium-ion battery [9] This case shows that the local deformation can occur, if the heat cannot be controlled properly. As an overall overview, the maximum and the minimum temperature differences shouldn't exceed 5°C inside the battery [10].

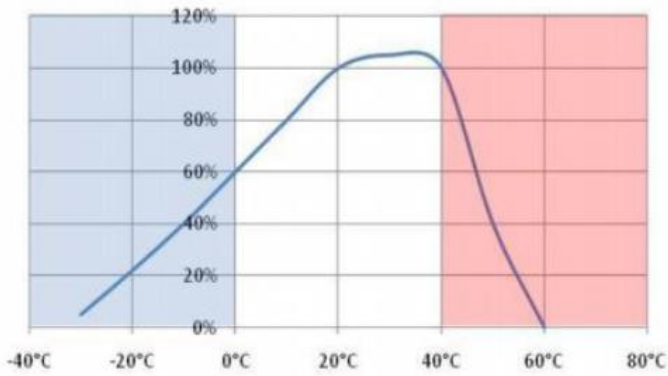
Therefore, BTMS carries an important role such as effective geometry of battery. Mohammadian et al.[11], found that using internal cooling methods provide effective way to balance temperature inside the battery. In this study, electrolyte is used as coolant inside the cell [12].

Many results show that battery performance is also poor under low temperature. Especially for many EVs, performance is affected from environmental temperature below -20 C. Nagasubramanian, studied 18650 type batteries with range of temperature -20 to 25°C. According to his research, the performance is affected %5 more from cold temperature comparing optimum operating temperature.

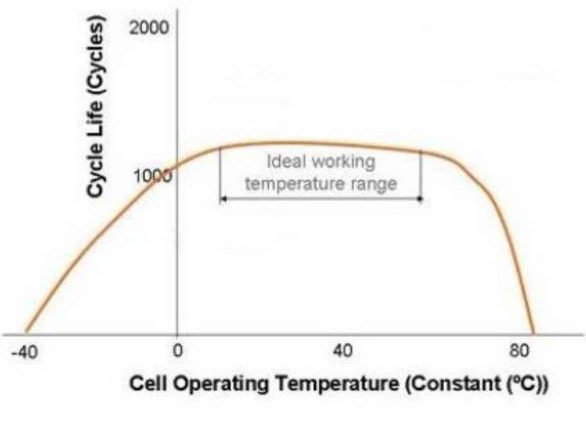
1.4.2. Operational Thermal Behavior of Battery

Thermal behavior of battery could both affect their own time cycle and performance directly. Therefore, it should be controlled to be between a specific temperature interval. As much as high temperature, cold temperature also should be taken into account while considering optimum temperature interval.

There are so many researches about finding optimum temperature of batteries.
15–35 °C and 20-40°C are defined as optimum temperature ranges. Matthe, et al [13] have found that maximum power of the battery and the maximum life cycle can be achieved around 30°C, which can be seen figure below.



(a)



(b)

Figure 6 (a)Temperature distribution and (b)life cycle of Li-ion battery [14].

1.5. Battery Thermal Management Systems

As discussed in the previous section, improper temperature affects battery badly, performance degradation and thermal runaway are the main issues that must be controlled. Therefore, thermal management system should be integrated inside the battery pack. The integrated systems are called Battery Thermal Management System (BTMS). There are many kinds of BTMS application that are used in HEVs and EVs. Their practical purposes show some differences, and air, phase change material and liquid cooling are the most common types of BTMS application.

While adapting thermal management system inside the battery pack, weight cost, complexity, cost, assembly condition and reliability must be evaluated as the criteria.

1.5.1 Battery Heating

Although many researches have been focused battery cooling during the last five-year, battery heating carries crucial importance as important as battery cooling to measure of BTMS. The reason behind of this idea is that thermal runaway, one of greatest challenge to protect for battery, occurs when battery temperature is too high comparing with the ambient temperature.

Most of researches said that battery performance reduces significantly in cold environment. Therefore, heating performance is another criterion that defines the thermal management system performance. There a few criteria that affect selection of heat system for batteries are**;**

- Heating time,
- Power consumption
- Building and maintaining cost
- Integration with BTMS, such as space and weight.

Vlahinos and Peseran made an effective research that they compare several heating methods according to their heating time and power consumption. They found that a heating module within battery pack most efficient approach [15]. The core heating method has an advantageous with power consumption firstly. At this method, warm air flow to cell adjacent and with convective heat transfer, flowed air spreads over the battery surface. However, liquid materials are still trying to observe effect of performance on battery. It is obvious that If liquid thermal management system could control two different kind of liquids at the same time, it would be an effective thermal management system for EVs. Tesla company, the famous EVs producer, can control a few kinds of liquid in their BTMS.

Integrating air heating method creates a need of a tool that provide air flow inside the battery pack. A fan and heater create a power need and it wouldn't be simple solution for heating. Also, the integrity of system is getting complex with its own control circuit.

The key factor for designing effective BTMS is selection of batter so that it must be adapting its current frequency while increasing discharge rate. It is obvious that high discharge rate creates a huge temperature differences from core of the battery though its surface. Thus, cold environment temperature could be ineffectual inside the battery. It could be transmitted to advantages fluctuating current at discharge.

1.5.2. Battery Cooling

Cooling performance of the battery thermal management system carries high importance for the comparison of performance of in all BTMS.

Passive or Active cooling are the main branches of cooling system. Then the BTMS are categorized according to heat removal position inside the battery; internal or external cooling. Most of the applications are external cooling system. Their heat removal operations realized contacting with another heat sources. Heat conduction realize from high temperature reservoir to cold temperature reservoir.

On the other hand, many studies show that the highest heat can be shown at center of the battery, so application of internal cooling reacts more fast comparing to external cooling. However, its compactness is much more complex, and its reliability is much less than external cooling applications.

BTMS can be classified into liquid cooling, air cooling, phase change cooling and combined them. The details of all BTMSs will be given in this section and then the most suitable one will be focused, tested and evaluated.

1.5.2.1. Air Cooling

The most traditional approach in todays' commercial uses in HEVs and EVs is air cooling. The convection heat transfer is the main strategy to extract excessive heat from surface of a battery. Both forced and natural convection can be utilized together. Using natural air convection alone could fail to be the control strategy of the battery temperature directly since convection coefficient is less than forced air convection coefficient. However, to utilize forced air convection, cooling system needs installation of fans or blowers which makes the system more complex, more expensive and heavier. Nevertheless, forced air cooling is the more simple, lightweight and low-cost cooling method when compared to liquid cooling and phase change cooling techniques.

For the past few years, many air-cooling studies focused on changing geometry of battery pack, thermal model development and battery structure to increase efficiency of cooling performance. There are a few similar studies that focused on different duct geometries of air inlet and outlet. The most successful geometry has been found as tapered manifold shape which provide huge advantages against other geometries. Also pressure ventilation is considered in almost all studies in order to provide fast temperature reduction.

Sun and Dixon's study [16] proved that the tapered flow provides significant benefits in their experiment. They used three-dimensional thermal model and their study has been agreed to be the proof of the geometrical advantages by many researchers.

Using Aluminum porous metal foam is the other method that increases the efficiency of cooling. Due to high conductivity of Aluminum, cooling time of Aluminum is less than cooling time of the battery, so the cooling of contacting surface provides much more effective and reliable technique. Mohammadian [17] proposed the design of a special air-cooled thermal management strategy by placing pin blades on air flow channels for prismatic Li-ion cells. In their study, a lower and more homogeneous temperature range was obtained. They then placed an aluminum porous metal foam into the flow channels to further improve the thermal performance of Li-ion batteries [18]. In addition to the permeability and porosity of the metal foam, the effects of different parameters such as different design states, pin fin arrangements, ejection velocities, inlet air velocity and temperature, porous tip length were also investigated.

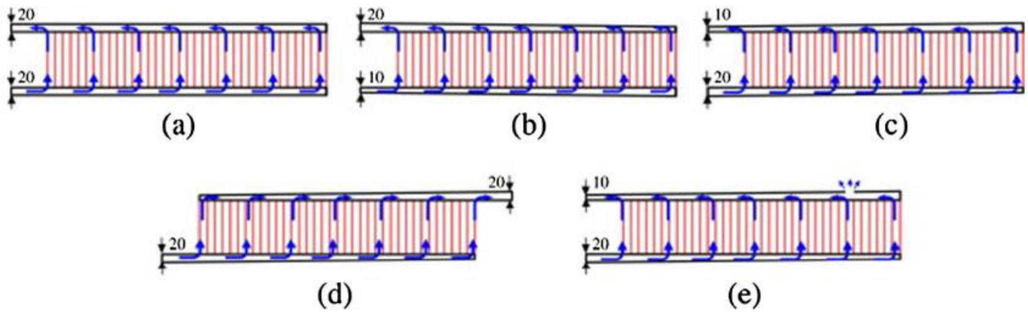


Figure 7 Different variations of Mohammadian’s air cooling experiment[18].

Although air cooling provides many advantages in aspects of low-cost, complexity and weight, its low thermal conductivity makes it unpreferable in many applications. Instead of air cooling, most of the biggest automobile brands prefer to develop more effective cooling by liquid and/ or phase change materials.

1.5.2.2. Liquid Cooling

Liquid coolant is an attractive option for BTMS. Thermal conductivity of liquid coolers is higher than that of air. Both natural and forced air cooling systems provide less effective cooling than liquid cooling strategies.

There are two main liquid cooling methods; direct and indirect liquid cooling. In direct cooling methods, battery is submerged to liquid dielectric coolant. In indirect cooling, cooling fluid flows in external geometry, such as tubular, jacket and micro channels. Heat is extracted from battery by cold contact surface that includes cooling flow inside the module. When compared, direct cooling has an advantage on cooling performance due to direct transfer of heat between coolant to contact surface of the battery module. However, dielectric fluid of direct cooling methods consumes higher power to obtain sufficient flow rates due to their high viscosity when compared to water in indirect cooling. Then it is the reason why bigger sized and thus expensive pumps are required for circulating dielectric fluid rather than circulating water in tubular geometry.

Chen et all [19] researched on the comparison of thermal performance of forced air cooling, fin cooling, indirect cooling and direct cooling and found that air cooling needs 2-3 times higher power consumption and indirect cooling has been found as the best option among others. Studies on direct cooling is very rare due to difficulties on practical applications.

There are a few common studies which have been made on prismatic cells to observe temperature effect with indirect cooling. Lan et al. [20] designed aluminum flat tubes surrounding prismatic cells. In this study, many micro-channels are placed to provide water flow over the cell. It is found that differences between maximum and minimum temperature is not very high. Additionally, Zhang et al.[21] applied aluminum tube surrounding prismatic cells like previous studies. however, they used additional flexible graphite that has high thermal conductivity in between tube and the cell. Surprising results have been obtained that maximum temperature differences can be minimized from 7 °C to 2 °C.

Another attractive idea for indirect fluid cooling is sandwich structure. In this method, researchers used two cooling modules that covers prismatic battery cell via its body. The cell is fully contacting the cooling module that includes cooling fluid, mostly water have been used. Although this method gives accurate and effective results, due to increased weighed and high power need to circulate cooling fluid, this method hasn't been applied in commercial automotive industry. Tong et all [22] used this method in their own study and they observed the effect of changing mass flow rate, number of micro-channels in module and plate wall thickness on average temperature change of prismatic cells. The most effective outcome has been obtained on cooling method geometry. The path of flow direction and number of micro-channels affect changing temperature directly. After this study, many studies focused on changed module geometries.

Entegrating a regular geometry inside the battery module is the most applicable method in industry. There is an alternative study have been made by Jin et all [23], they designed U-shape plate that consist of many micro-channels. This geometry provides some advantages in both decreasing power consumption and weight. After this study, such kind of geometries was tried many times. Serpentine cooling channels can be shown as an example for regular geometries. Today, one of the most successful applied cooling methods in industry, which is the cooling system of Tesla, consists of serpentine tubes which circulate metal oil inside. Jarett and Kim[24] made an detailed research on the mathematical algorithm of serpentine cooling channels. This research also enlightens the relation between pressure drop and temperature change.

In addition to researches and advancements on cooling path and cooling geometry, liquid properties have been also investigated. Al_2O_3 and hydrogel were tried in many researches for BTMS. Huo and Zhao [25] found that adding 4 percent Al_2O_3 on water mixture decreased the battery absolute temperature by %7 compared to pure water circulation. Yang et all [8] showed that circulating liquid metal gives more effective results compared to water circulation. Zhao and Zhang et al. [26] proposed circulating hydrogel inside tubes and their results have been confirmed with both simulation and experiment positively compared to pure water.

One of the most effective cooling systems has been created by Tesla includes serpentine geometry consisting of Aluminum coating with dielectric metal. This tube structure covers the cylindrical battery bundles, which can be seen in Figure 8 below. In addition, as mentioned above, they are using glycerol mixture with water. Freezing point of the mixture is lower than water, so it can be more adaptable against cold environment.

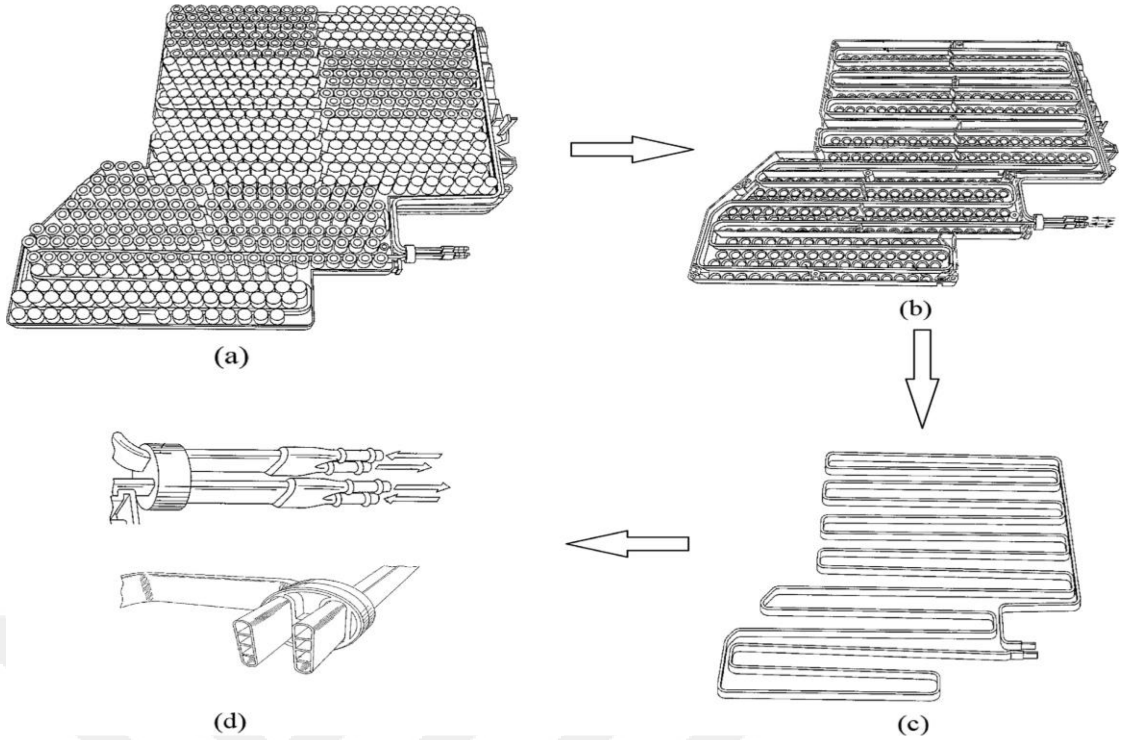


Figure 8 Schematic of liquid BTMS used in Tesla: (a) the cooling tube inter-engaged with a sheet of cells; (b) the cooling tube setup; (c) the cooling tube; (d) the side view and end view of the inlet and outlet [22].

1.5.2.3. Phase Change Cooling

Above presented cooling methods, active air cooling and liquid cooling, both extract heat via convection from generated surfaces. Because of that, circulation carries high importance for BTMS efficiency. Therefore, there is a need for power consuming devices in order to maintain circulation of material such as; ducts, fans, pumps and valves. Those devices utilize extra power and increase cost which is the restriction criteria for decreasing efficiency of BTMS. Therefore, during the past ten years, many researches have been conducted in order to find new methods including passive cooling. Phase change cooling is the most attractive option for passive cooling technologies.

The main phenomena for the working principal of PHMs is based on following main physical stages. In nature, matters exist in 3 different phases; solid, liquid and gas. During transformation from solid to liquid or liquid to gas, the energy is absorbed due to nature of phase change since during phase change, molecular energy increase or decrease accordingly. This specification can be adjusted to heat dissipation for battery to extract heat from battery. In this thesis, liquid-vapor phase change process will be considered in detail due to common usage in industry.

Boiling management system is one of preferred method for passive cooling. In this method, phase changed material is involved in heat transfer phase. Generally, liquid to gas stage have been studied in many research papers. Bandhauer [27] has reviewed BTMS using phase change material in micro channel tubes. This is one of the greatest researches for phase change material since it reflects many open points to search alternative storage ways. R134a was used as phase change material for his proposal. For this proposal, condenser was used to change phase of R134a from vapor to liquid stage during storage. There are a few different approaches on boiling method. One proposal has been suggested by Gils et al.[28], which is covering battery by dielectric phase change material. He used boiling method for phase change material to pass from liquid to gas stage. The same method has been applied by Hirano et al., they used sandwich type structure, prismatic cell is covered with porous materials and plastic. Hydrofluoroether liquid and vapor flow though around this structure. The result is very surprising that maximum temperature can be held around 35°C at 20C discharge rate. In Figure 9 below, typical heat pipe which carries phase change material has been illustrated[29].

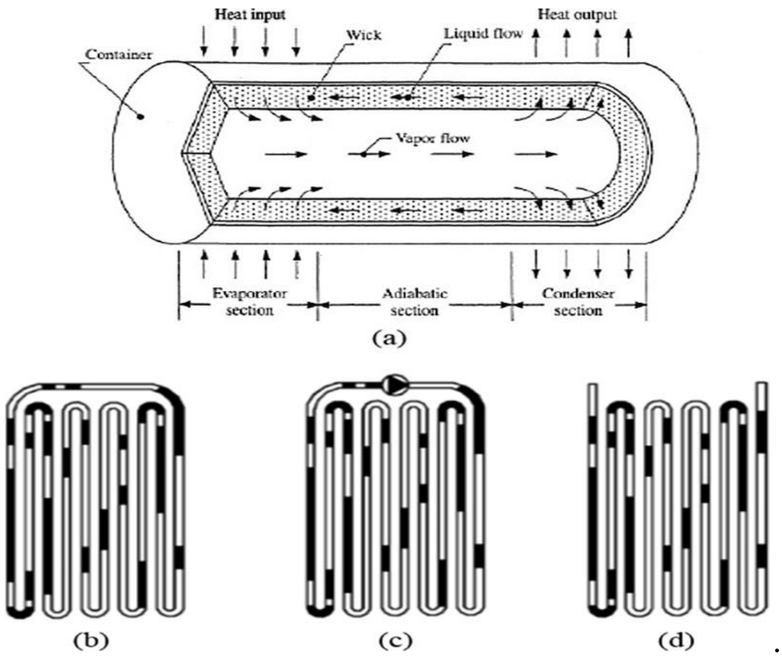


Figure 9 Working structures of (a) capillary heat pipe and different PHPs: (b) looped; (c) looped with check (d) open continuous circulation[3].

In Figure 9 above, the heat pipe consists of two main structures. First is cooling fluid and the other one is protected container structure. This structure includes wick on the inner surface. Wick structure can be obtaining from metal powder with sintering, which is thermal process application for power methodology. The heat pipe also can be categorized into 3 different section according to their tasks; evaporator section, adiabatic section and condenser section.

While circulating working fluid, the heat flux is transmitted from container into evaporator for working fluid to change phase. After that, working fluid transform to vapor phase. While circulating, heat is carried by vapor of fluid. This phase will continue until reaching to condenser. It is kind of cooling process to obtain fluid phase in the circulation system. To complete thermodynamic cycle, the liquid state again moves to evaporator. While moving from condenser to evaporator, due to pressure differences, capillary force is formed in the pipe.

There are some advantages of using heat pipe in cooling system; they are low cost equipment; no maintenance is required, and they have great thermal conductivity. Therefore, heat pipes are preferred in many industries, such as spacecrafts, solar panels and nuclear plants.

On the other hand, using heat pipes for BTMS in EVs isn't preferred way as much as other industries and the investigation of heat pipes in BTMS hasn't been fully reviewed yet. Rao et al.[30] have obtained some results that don't satisfy cooling performance. According to this research, temperature can be held below than 50 °C with consuming 50W. They made this investigation using 4 copper pipes. Although the performance can increase with number of pipes used, the energy consumed can't compensate this correlation comparing with indirect liquid cooling. Therefore, this is one of biggest reasons why liquid cooling is preferred in EVs industry instead of PCMs.

As described earlier, working fluid is the key factor to describe the thermal performance of phase cooling. There are some studies to observe effects of different types of working fluids on the performance BTMS. Distilled water, alcohol and acetone are studied and compared with each other by Putra [31]. Performance effect on the thermal behavior of the battery has been affected by using acetone positively. Besides acetone, n-pantane is other effective phase change fluid that was tried in many studies. If the environmental conditions of battery need high thermal power load, water and methanol would be more appropriate working fluids compared to acetone.

Additional to type of working fluid, effect of condenser is also important parameter for the BTMS. In literature, a few kinds of cooling storage ways have been defined. One study was presented by Ye et al. where quenching method was used and greatest effort was spent to show details of study.

A better performance was also achieved in the study of Burban et all.[32], where they studied efficient condenser position in BTMS. The condenser was placed on the evaporator. The key point of this method is that heat pipes must be contacted well to surface of the battery. The conduction area is proportional to extracted heat from heat source. One great advancement in using heat pipes is that, it can be studied analytically. Many other phase change studies are conducted by experimental methods. Therefore, heat pipe method in phase change cooling is open to be progressed before deciding final BTMS. It can be progressed with R&D methods.

To sum up, advancement in liquid to gas phase change cooling BTMS have been investigated recently and higher heat dissipation coefficients have been obtained in liquid-vapor transition compared to single phase liquid convection cooling. Boiling effect also presents an alternative way for phase change BTMS, but it must be promoted by tangible researches for next generations. Heat pipe base BTMS is the most applicable method and a few examples for this method could be achieved in industry. Also, numerical model can be provided in heat pipe BTMS, so correlations can be provided with experimentation.

Until now, liquid-vapor PCM, boiling method and heat pipe method have been reviewed and illustrated by many researches. Apart from those methods, solid to liquid phase change cooling can be evaluated as alternative BTMS. By many authorities, boiling and heat pipe methods have been classified as passive liquid cooling method. PCM thermal management systems are much simpler for assembly in battery pack, there is not any need for circulation inside the battery so PCM BTMS is also classified as passive cooling method.

To construct PCM for battery thermal management system, selection of chemical substance is of crucial importance. Rao and Wang have defined the requirements for selection of PCM in their research. Today, those requirements are still protecting their worth to design efficient BTMS for using with PCM. Their points are;

- A desirable temperature range of the scope for melting of material should be defined.
- Heat conductivity and heat capacity must be considered.
- Small extension coefficient for transition state is required.
- Freezing, sub-cooling effect must have small effect.
- Advantageous from economical prospective.
- Hazardous effect must be considered during changing of phase.

For all PCMs, conduction is the way of heat transportation. While PCM melts, material has absorbed all heat flux from surface of battery via conduction. As defined in above statements, melting point carries high importance against extraction of heat flux from heat source, because after transition from solid state to liquid state, PCM absorbs heat. Yan et al.[33] has discovered that ideal phase change temperature should start at 30-50°C. One of the greatest advantageous of using solid phase change material is preventing thermal runaway inside the battery. Paraffin is the most preferred material for phase change BTMS since melting point of paraffin could be extended with adding alkane metals. This provides to shape BTMS for designer in the line of system requirements. Therefore, after adding some metals, it is possible to see many kinds of research with using different kinds of paraffin mixture.

Despite the advantages mentioned above, the biggest challenge for using PCM is interfering directly to where system reaches maximum temperature. Interfere speed is very low for every PCM, because of its nature, having a low thermal conductivity. In most of researches related with PCMs, the maximum value of thermal conductivity has been accepted as 0.4 W/m K which is the most important parameter for defining thermal transportation inside the battery.

There are a lot of examples in the literature including studies on increasing thermal conductivity of PCMs. First method is the decomposition of thermally conductive materials, such as graphene, nanoparticles, and carbon into PCM. Second method is adding porous material; such as metal foam or metal ingredient including porosity structure. Third way is very similar to second way, using metal sheets or metal fins. Adding carbon fibers to PCM mixture is the most common method to enhance performance of cooling effect of PCMs. There is an important study that shows the positive effect of carbon fibers clearly, by Samimi et al. [34]. They found that carbon fibers have enhanced the performance of PCMs two times. Babapoor et al.[35] also found the effect of adding carbon fibers associated with mass fraction ratio over total weight of PCM. Adding of 0,46 wt % carbon fiber gives almost ten thousand times higher results comparing with paraffin waxes.

Saturating PCM in porous media becomes more attractive method over past few years. It is a method for not only increasing thermal performance and also a way to increase mechanical properties by being a skeleton for a body, studied by Qu et all [36].

1.5.2.4 Thermoelectric Cooling

For improving cooling or heating effect of BTMS, thermoelectric cooling is a distinctive way compared to others. In this method cooling, or heating cannot be used on its own inside the battery, it requires one more way to transfer heat flux on battery surface. It is not easy to find literature on this method, since its application is based on last 3 years, but in special brands, Valeo, which is one of the famous suppliers for automotive industry, developed a new product that includes thermoelectric chip.

The thermoelectric chip, which can be seen in Figure 10 below, consists of two different semiconductors, n-type and p-type, between ceramic plates. Sizes of thermoelectric chips vary, but the most common used types are between 80 mm^2 and 200mm^2, very small portion compared to battery pack.

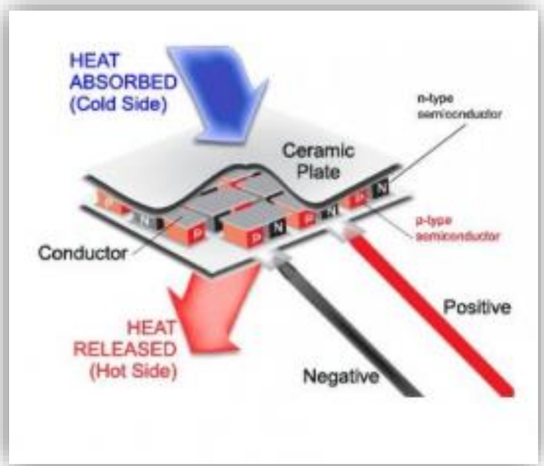


Figure 10 Thermoelectric chips and sample shown of its structure[37].

While DC electric current flows through the device, the chip works, and heat is transferred to reverse direction on the other surface. This is the basic working principle of thermoelectric chip. It is also called as Peltier effect in many researches.

Using thermoelectrical chips on the battery surface is very successful operation to transfer and to extract heat flux from hotter surface of a battery.

Moreover, to design an effective BTMS could be more advantageous with thermoelectric chips. Generally, air cooling and heat pipe cooling could be suggested with this method. Despite the lack of some researches on literature, many companies have initiated advance R&D potential to improve their BTMS with Peltier effect.

One of the example studies of Mahle Company can be seen on Figure 11 below. They prefer to use integrated liquid module with its own thermoelectrical chips assembled below the battery pack. In this illustration, it could be seen that heat flux can be transferred from battery surface to liquid cooling module, via thermoelectric chips. What is important is that heat flux could be cooled more easily in this module instead of creating on battery pack. Liquid inlet and outlet were designed perfectly to provide steady flow, the mass flow rate could be adjusted according to cooling requirement.

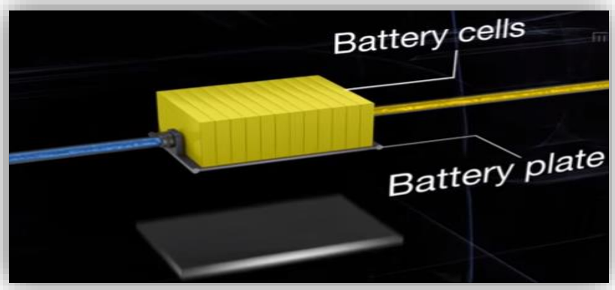


Figure 11 Mahle's cooling solution without thermoelectric chip integrated to the battery pack [38].

As seen from the Figure 11, BTMS has been provided with liquid pipe cooling, and circulation of fluid is realized in bottom plate, which is shown on below figure with more details. Thermoelectrical chips have been assembled on bottom plate. With this method, instead of direct contact surface between pipe and plate, thermoelectric chips increase to tear heat flux from battery cell. According to studies, thermoelectric chip increases the cooling rate more than %28 compared to traditional liquid cooling.

One of the greatest difficulties for using thermoelectric chips are that their geometry is not convenient to use with cylindrical batteries. In automotive industry, 90% of EVs are using cylindrical batteries in battery packs. Unlike automotive industry, there is no any specific geometry for thermoelectric chips, and chips can be found as prismatic geometries.

Due to above reason, experimented thermoelectric chips were used with prismatic cells and since our cases include cylindrical battery pack, using thermoelectrichips could be inappropriate for BTMS. Thermoelectrichips are quite open to improvement and the geometrically restrictions hopefully will be eliminated with technological improvements.

Figure 12 Mahle's cooling solution using with thermoelectric chips entegreted to the battey pack [38].

1.5.3. Comparison of Different Cooling Systems

Many studies have been focused on BTMS to increase performance of battery capacity and its power, on last decades. It has been proven that battery working temperature strongly affects power capacity, life cycle, and failures for batteries. It might even cause the thermal runaway where temperature increases improperly inside the battery. Large temperature differences among the cells also affect battery power capacity negatively, despite having an insufficient BTMS. Therefore, it has been cleared in many studies that optimal battery temperature should be in operating temperature variation of 20-55°C. To sum up, having an effective BTMS inside the battery, is the key factor to control desired temperature and increase power capacity and life cycle of Li-ion batteries.

There are different kinds of battery thermal management systems which are already defined in above sections. These are carrying vital importance for a battery to ensure its performance. In above sections, cooling kinds are classified as passive or active air and liquid cooling, phase change cooling, and thermoelectric cooling. Among these methods, the air and liquid cooling are most preferred methods over others. The reason is that, active air-cooling needs low cost, simplicity, availability and easy to maintain operational requirements. Even tough studies focused to change geometrical layout of air ducts inside the battery to enhance its natural poor thermal performance in recent years, results caused to change strategy to move on with different cooling methods. Table 3 shows advantages and disadvantages of different applications of BTMSs. The most convenient application for EVs consist of cylindrical cells may be decided among these methods.

Table 3 Comparison of different cooling methods

	Advantages	Disadvantages
Air Cooling (Forced)	• Low system and maintenance cost • High lifespan • Easily used for heating • Applicable for almost each size of battery pack • Commercial application	• Low thermal performance • Low temperature uniformity • Low efficiency • Additional power consumption device is necessary

Liquid Cooling	• High temperature drops • Fast reaction • Highly efficient • Applicable for each battery cell • Temperature controlled uniformly • Efficient for heating • Commercial application	• High cost • Extra weight • Additional power consumption device is necessary
PCM Cooling	• Low cost • Large temperature absorption • High lifespan • High energy storage capacity	• Not suitable for prismatic cells • Poor thermal conductivity • Extra weight • Volume expansion • Existing leakage risks • Flowability • Not commercial • Difficulties for maintenance
Thermo-Electric Cooling	• Effective thermal performance • Highly conductive device • Less weight • Could be used for heating	• Not suitable for cylindrical batteries • Needs extra cooling methods • Changes only heat flux surface

Despite the many advantages of Phase Change Material cooling, application of this method is quite challenging. Large necessary volume need is the greatest challenge for using it inside the battery. Safety issue is another concern for PCM. If leakage problem doesn't ensure to be safe side, it would cause inevitable problems. Explosion or stopping of a battery pack must be taken into account.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 Analysis of Thermal Behavior of Batteries

Energy conversation is the first step to formulate heat operation and energy balance equations; as shown in Eq. (1) which defines the temperature distribution within the battery.

$$\rho_b C_{p_b} \frac{\partial T_b}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_r r \frac{\partial T_b}{\partial t}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda_\varphi \frac{\partial T_b}{\partial \varphi}\right) + \frac{\partial}{\partial Z}\left(\lambda_Z \frac{\partial T_b}{\partial Z}\right) + \dot{Q}_b \tag{1}$$

In Eq. (1) the convective heat transfer inside the battery has been omitted, heat generation of the battery is formulated with very complex equation. Heat generation inside the Li-ion battery consist of reversible and irreversible heat mainly. The reversible heat is occurred due to change of entropy inside of the battery. Especially, electro-chemical reactions trigger the entropy change. This is also known as entropic heat. The irreversible heat occurs due to relation of polarization and ohmic heat. The polarization can be measured by how many cell open circuits potential deviate from operating potential. In nature of chemical process of inside the battery, there is always a barrier at solid electrolyte to hinder charge transfer. The energy that is provided to overcome this barrier is called active polarization heat. The ohmic heat can be modeled by the energy that is lost during transport resistance[3].

There are different approaches to formulate energy generation of the battery. However, Liu et all, summarize the simplified heat generation model by electro-chemical analysis. It can be seen Eq 3 below. The first term of the equation is formulation of polarization heat equation, second term is entropy reaction heat source. The third one is ohmic heat source which is energy loss due to transportation of electrons and last two terms are ohmic heat sources consist of impedance and transporting loss in electrolyte phase.

$$\dot{Q}_b = a_s i_n(\emptyset_s - \emptyset_e - U_{OC}) + a_s i_n\left(T\frac{\partial U}{\partial T}\right) + \sigma^{eff}(\nabla\emptyset_s)^2 + k^{eff}(\nabla\emptyset_s)^2 + \frac{2R_gTk^{eff}}{F}(t_+^0 - 1)\left(1 + \frac{dlnf_\pm}{dlnc_e}\right)\nabla lnc_e\nabla\emptyset_c \tag{2}$$

Even tough above equation gives precise results and includes all excessive electro-chemical parameters, the simplified equation was proposed by Bernardi et al. [39] Both charge potential and ohmic loss transmit in one term, first term left side the equation, it can be seen below in eq 4;

$$\dot{Q}_b = I(U_{OC} - V) - I(T\frac{dU_{OC}}{dT}) \tag{3}$$

In their recently study, Karimi and Li, found experimental formulation. They made experiment on SONY- US18650G3. The general heat generation can be found with equation below with following empirical correlations;

$$\dot{q} = R_i i^2 - iT\frac{\Delta S}{nF} \tag{4}$$

$$R_i = \begin{cases} 2.258\times 10^{-6}SOC^{-0,3952},\ T \le 20°C \\ 1.857\times 10^{-6}SOC^{-0,287},\ T \le 30°C \\ 1.659\times 10^{-6}SOC^{-0.162},\ T \le 40°C \end{cases} \tag{5.1}$$

$$\Delta S = \begin{cases} 99.89SOC - 76{,}67,\ 0 \le SOCT \le 0.77 \\ 30,\ 0.77 < SOC < 0.87 \\ -20,\ 70.87 < SOC \le 1 \end{cases} \tag{5.2}$$

Where $SOC = 1 - \frac{it}{C_0}$

Equation 5 defines heat generation rate based on empirical formulations. This can provide benefit while calculating local heat generation over the battery. In order to solve above equation, boundary condition must be defined as follows for radiation and convection boundary.

$$-\lambda \frac{\partial T}{\partial n} = h_s(T - T_{amb}) + \varepsilon\sigma(T^4 - T_{amb}^4) \tag{6}$$

To simply calculation, radiation heat transfer equations are adopted to Newton's cooling's law. The radiation is recognized by connective heat transfer coefficient.

$$h_{rad} = \frac{\varepsilon\sigma(T^4 - T_{amb}^4)}{T - T_{amb}} \cong 4\varepsilon\sigma T_{amb} \tag{7}$$

The simplest heat transfer equation can be obtained below.

$$-\lambda \frac{\partial T}{\partial n} = h_s(T - T_{amb}) + h_{rad}(T - T_{amb}) = h_t(T - T_{amb}) \tag{8}$$

To create heat transfer equation between battery and circulated liquid water cooler, energy equation of water must be defined how it was done like battery above paragraph. For battery side, equation has been shown as $\dot{Q}_b(\dot{Q}_{battery})$, water energy equations will be shown as $\dot{Q}_W(\dot{Q}_{Water})$.

$$\rho_W C_w \frac{\partial T_w}{\partial t} + \nabla\left(\rho_W C_w \vec{v} T_W\right) = \nabla(k_W \nabla T_W) \tag{9}$$

$\rho_W C_w$ and k_W are density, specific heat and thermal conductivity of battery respectively. Others are water temperature and velocity factor.

To solve energy equation, continuity equation and momentum conservation must be solved under the energy equation;

$$\nabla . \vec{v} = 0 \tag{10}$$

$$\rho_W \frac{d\vec{v}}{dt} = -\nabla \mathrm{p} + \mu \nabla^2 \vec{v} \tag{11}$$

P and μ defines static and dynamic viscosity of water in the energy equation.

CHAPTER 3

METHODOLOGY

During the study, all BTMS are reviewed in literature, and different methods are compared with each other and applications from literature. After the selection of the type of the BTMS, different designed configurations are studied and compared with each other. The main purpose of the thesis is to evaluate the best design to improve BTMS performance in line of computational and experimental studies.

3.1. Selection of Type of Battery Thermal Management System

Phase change material and thermo electrical cooling are quite new methods compared to others. There are not much available industrial applications for both of PCM and thermoelectrical cooling, despite existing many theoretical studies. Due to their reliability and being open to be improved, forced air cooling and active liquid cooling systems are mostly available in industrial applications. Below, drawbacks of PCM and thermoelectrical cooling are explained in detail, and the selection of the type of cooling system is explained logically.

From all technical perspective; for PCM cooling, even under high ambient temperatures around 50°C, the temperature inside the cell pack is always below than the ambient temperature because of high thermal conductivity and latent heat[40]. When the temperature of the battery pack is higher than the temperature of the PCM melting point, heat is stored as latent heat and is then released to the module of battery when the ambient temperature is lower than the temperature of the PCM melting point[41]. Also, having a potential of flammability due to the characteristic of the PCM-graphite, safety concerns keep it at backstage of its performance effect.

Thermo-electric modules are low efficient heat transfer devices. The greatest weakness of the method is that, the highest efficiency is up to 0.8 % which means more power is needed than heat dissipated[42]. The performance of cooling system is related to the required temperature difference. That means if the temperature of battery doesn't spread equally on its surface, then thermo-electric chips would be insufficient.

Air cooling on the other hand, may not be so effective when big amounts of heat is to be dissipated regarding the low heat capacity of air and the size of the fans.

In the light of comparison of performance of listed methods above, the decision for the type of battery thermal management system is done on active liquid cooling for improving BTMS in the current study. 12 different experimental research studies have been examined and taken as reference to decide on the selection of liquid cooling geometry and type. Also, state of the art research has been done and several common industrial applications have been considered among the selection procedure for the BTMS regarding geometry and material type.

3.2 Selection of Type of Cooling System

For the liquid cooling BTMS of the study, geometric design has been evaluated with two different alternative cooling types. Decision matrix was created between these alternatives based on industrial applications in the light of the information and studied parameters. These two alternative design drafts could be seen in figures at section 4.2. Common liquid cooling structures consist of Aluminum blocks or jacket. Due to its electrically non-conductive and heat conductive behavior, Aluminum is mostly preferred material for covering battery packs. Generally, circulation of cooling liquid is transferred with different pipes or canals. There are a few examples of thermal management systems which belong to famous manufacturers shown in the illustrations below.

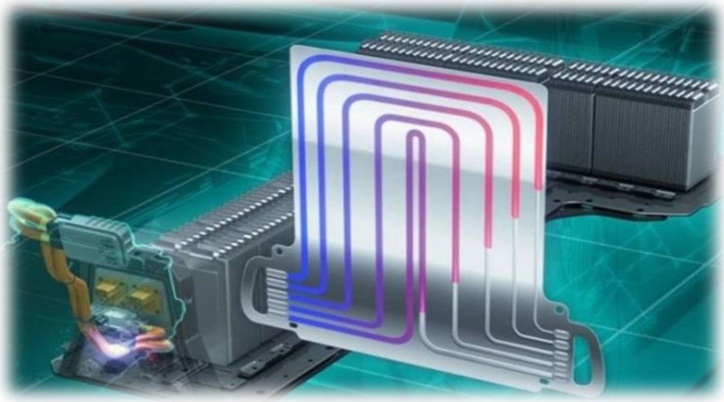


Figure 13 Example for GM BTMS [43]

In Figure 13, Chevrolet’s liquid battery cooling method can be seen- heat transfer liquid that passing through a canal through fins. Many of the fins are in the battery regularly, so penetration of battery cells to liquid plate has been targeted to benefit higher efficiency. However, the battery pack consist of many prismatic cells so its cooling efficiency could be increased with fin geometry, when cylindrical batteries are considered.

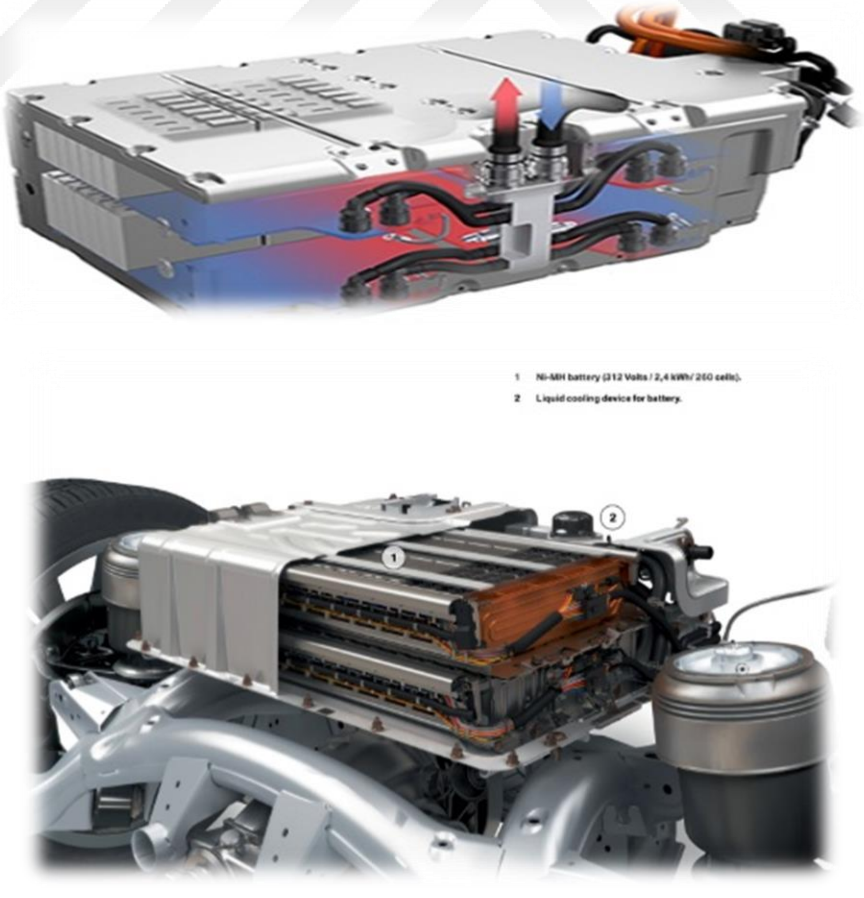


Figure 14 BMW ActiveHybrid X6 high voltage battery pack [44].

In Figure 14, BMW's battery pack has been covered with aluminum frame and liquid canal is directly contacting the battery pack. Prismatic cells have been fixed with regular distance in aluminum frame. This illustration could be separated from other aspect of using fluid flow. After leaking into sup pipes from main pipes, liquid has been distributed through a plate. Instead of cooling vertical direction, liquid flow passes bottom side of battery, so this example could be considered as unusual method for BTMS.

In most successful and long-life battery packs, BTMS have been designed commonly by aluminum frame and copper pipes. While designing alternative methods, researches have preferably chosen to work with aluminum frame and copper pipes.

3.3 Selection of Cooling Geometry and Material for BTMS

After reviewing some industrial applications and literature, two main geometries have been evaluated and compared. While comparing geometries, each method has been evaluated considering different geometries with different methods, so, there are 4 different methods placed in the decision matrix of the tests.

Pugh Matrix has been used as decision matrix and all 4 different alternatives have been graded in the matrix which can be shown in Table 4 below.

When the heat transfer methods are examined, it is crystal-clear fact that; the greater the penetration between the cooling source and the thermal source, the more effective performance is obtained. Therefore, draft geometries have been based on this idea to build a BTMS.

Alternative geometries could be seen in figures below. Aluminum block has been preferred for the body in both cases. As mentioned in previous sections, its advantages are that heat could be easily transferred in hot surface to cold surface or vice-verse. Then liquid water has been selected as circulation fluid based on findings from similar experiments from the literature, which have been considered in previous parts of the study.

The first alternative geometry can be seen in Figure 15 below. Two different options have been evaluated in the design, which are horizontal or vertical pipe cooling. Pipe material has been selected as copper, which is highly capable for conducted cooling liquid. Pipes surround aluminum block with regular distances so that heat could spread steady over the battery. Those geometries have been considered in the decision matrix as concept 1 and concept 2 and compared.

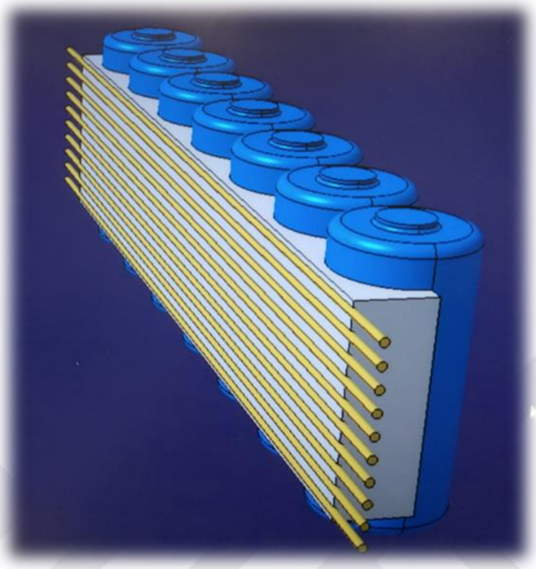


Figure 15 Alternative geometry option 1

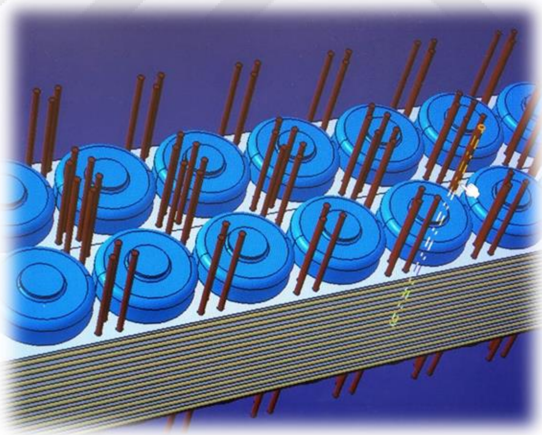


Figure 16 Alternative geometry option 2

Other types alternative to first two concepts considered can be seen in Figure 17 and 18 below. PCM cooled channels are considered for the third concept and liquid water-cooled channel is considered as the fourth concept. For the main body of the channel, a symmetrical aluminum plate is designed. Connecting of these two shapes with bonding material, the channel geometry can be seen in Figure 17 below. Yellow and blue plates are bonded with each other and the channel created could be filled with

PCM (Alternative geometry option 3) or circulating fluid (water) (Alternative geometry option 4).

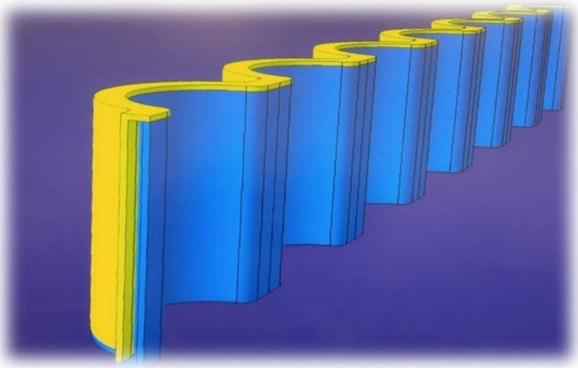


Figure 17 Alternative geometry option 3

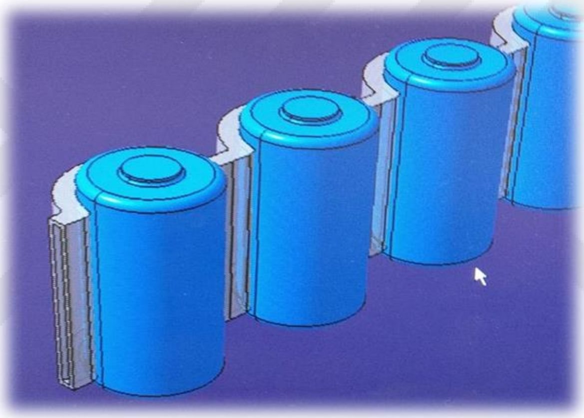


Figure 18 Alternative geometry option 4

Table 4 Pugh decision matrix

Pugh Matrix

Alternatives	Baseline	Long Life Cycle	Easy to Assemble	Performance	Weight	Reaction Speed	Safety	Sustainability	Totals	Rank
Concept 1	1	1	1	0	1	1	0	1	5	1
Concept 2	1	1	1	0	1	1	0	1	5	1
Concept 3	-1	0	-1	-1	-1	0	-1	0	-4	4
Concept 4	0	0	-1	1	0	1	0	1	2	3

Values
▼ -1
○ 0
▲ 1

Comments: All concepts have been evaluated between 7 different criteria. Concept 1 and 2 have the greatest rating on the decision matrix.
Concept 1 and 2 have been selected as the BTMS
Concept 1 and 2 will be compared with other on the next sections

Concept 1: Horizantal pipe cooling
Concept 2: Vertical pipe cooling
Concept 3: Filled with PCM cooling between aluminium plates
Concept 4: Liquid circulation cooling through alumium plates or canal

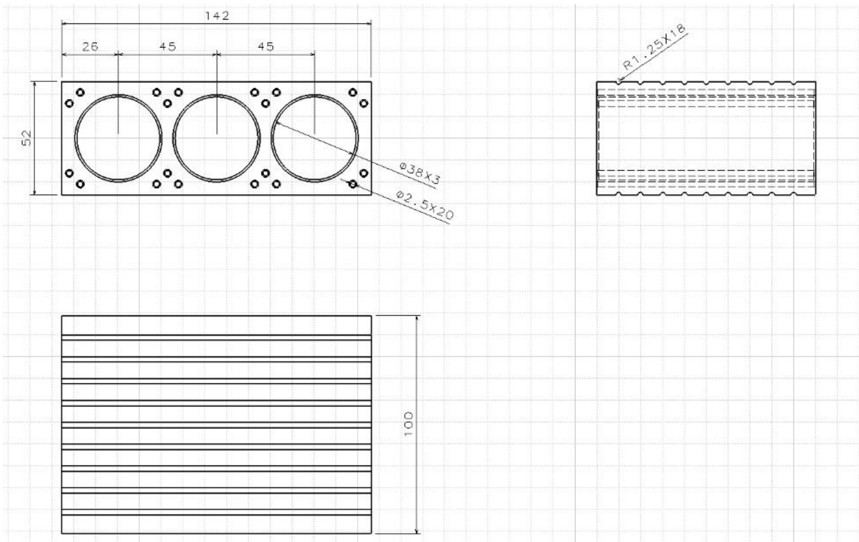
As seen from above Table 4, 4 different concepts have been compared and first draft design for BTMS has been selected.

3.4. Numerical Analysis

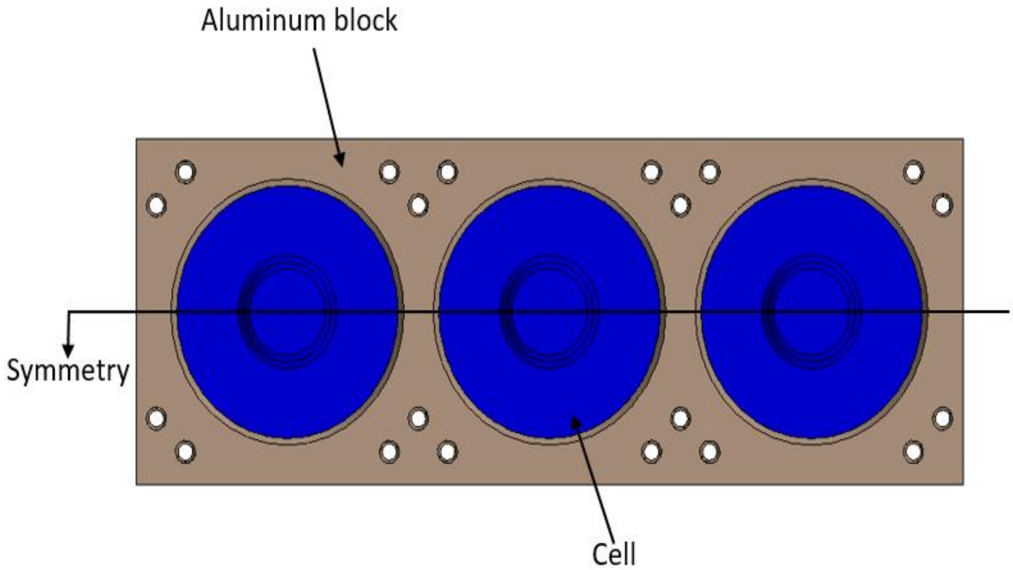
In this study, concept 1 and concept 2 are numerically evaluated according to the results of Pugh's matrix. Cylindrical lithium-ion battery module is cooled with water at different channel directions and variable water velocity conditions in order to decide which one is more efficient for cooling performance. The cooling phenomena is based on an effective heat transfer methodology from battery to cooling water with the aluminum block.

3D Conjugate Heat Transfer (CFT-CHT) analyses are performed in this study with using STAR CCM+ software. As a first step of the study, two different solid domain and one fluid domain has been created. In Figure 19, illustration for three cells and the aluminum block can be seen. For the CHT analyses, half of the domain which is shown in Figure 19 is used as the computational domain and centerline is specified as symmetry boundary condition. Laminar flow has been simulated. According to unsteady assumption, time step has been defined as 0,5s and inner iteration has been defined as 5. First, vertical cooling has been tried with closing other channels, than same methodology has been applied to horizontal cooling. Mesh study have been examined with increasing number of meshes 4 times higher. As seen in next figures, differences between coarse and fine meshes is %16, on the other hand, differences between medium and fine meshes is %5. Therefore, all analysis has been performed according to medium mesh.

As assumptions during the simulations, entire module is in an adiabatic environment, a thermal insulating boundary was applied. Thermal contact resistance hasn't been considered in this study. Inlet water temperature was set to 22℃, equal to ambient temperature.



(a)



(b)

Figure 19 (a) Batter module dimensions (**b)**Battery module of analyzed geometry

Firstly, horizontal cooling channels were used to cool the battery module with different inlet water flow rates. After that, vertical cooling channels were activated, and horizontal channels were inactivated. In order to investigate the effects of channel direction on the cooling process, both horizontal and vertical channels were never used at the same time. The cooling channels are shown in Figure 20.

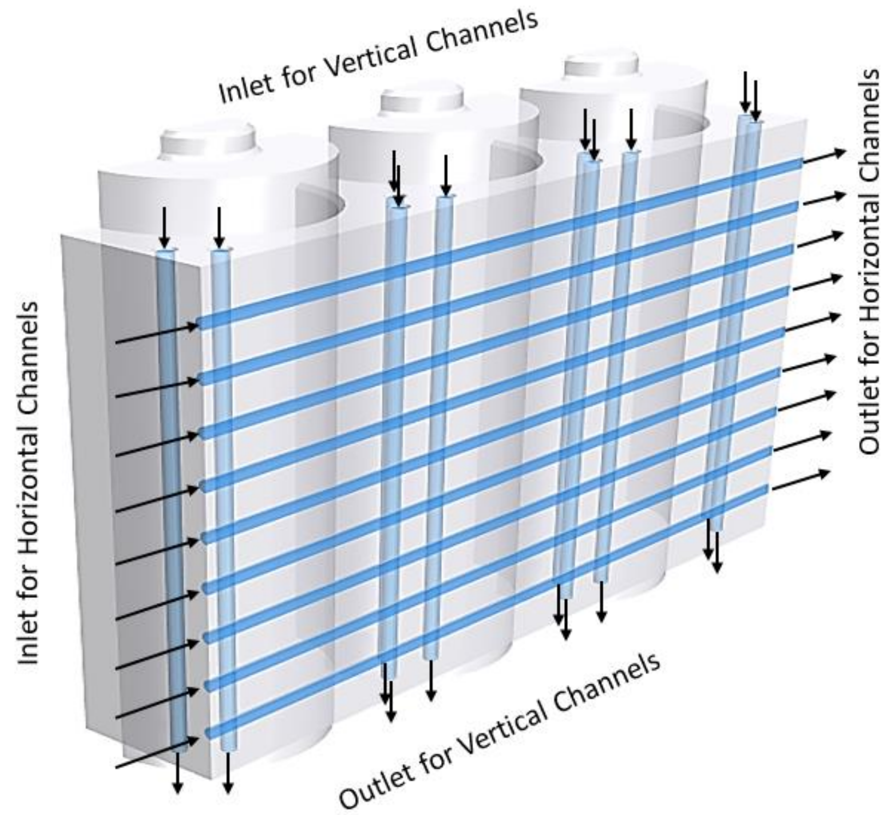


Figure 20 Horizontal and Vertical Cooling Channels of the Battery Module

For the computations, tetrahedral type cells are used and to reach mesh independency the analyses are accomplished at different mesh numbers.

3.4.1. Boundary Conditions and Material Properties

Material properties of analyzed geometry which are the input initial values can be seen in Table 5 below. Table 6 shows the boundary conditions.

Table 5 Material properties of tested geometry

Material	ρ ($kg.m^{-3}$)	c ($J.kg^{-1}. K^{-1}$)	k ($W.m^{-1}K^{-1}$)	μ (Pa. s)
Aluminum	2719	871	202.4	-
Battery	2500	1200	4	-
Water	998.2	4128	0.6	1.003×10^{-3}

Table 6 Boundary conditions for analyzed geometry

Boundary	Type	Parameters
Aluminum wall	Adiabatic	q =0 w/m^2
Water inlet	Velocity inlet	0.05-0.4 m/s, T=25^oC
Water outlet	Pressure outlet	1 bar, T=25^oC

Analysis are mainly done under different discharge rates because, discharge rate is an important characteristic for a battery that causes heat production and it directly affects its thermal performance behavior. The value of discharge rates is taken from its datasheet of battery depending on time. The heat generation rates have been used as variable heat sources while analyzing thermal performance of BTMS of concept 1 and concept 2.

3.4.2. Mesh Independency Study

For the computations, tetrahedral type cells are used and to reach mesh independency the analyses are accomplished at different mesh numbers. In Figure 21, grid scenes are shown, and grid numbers are given in Table 7.

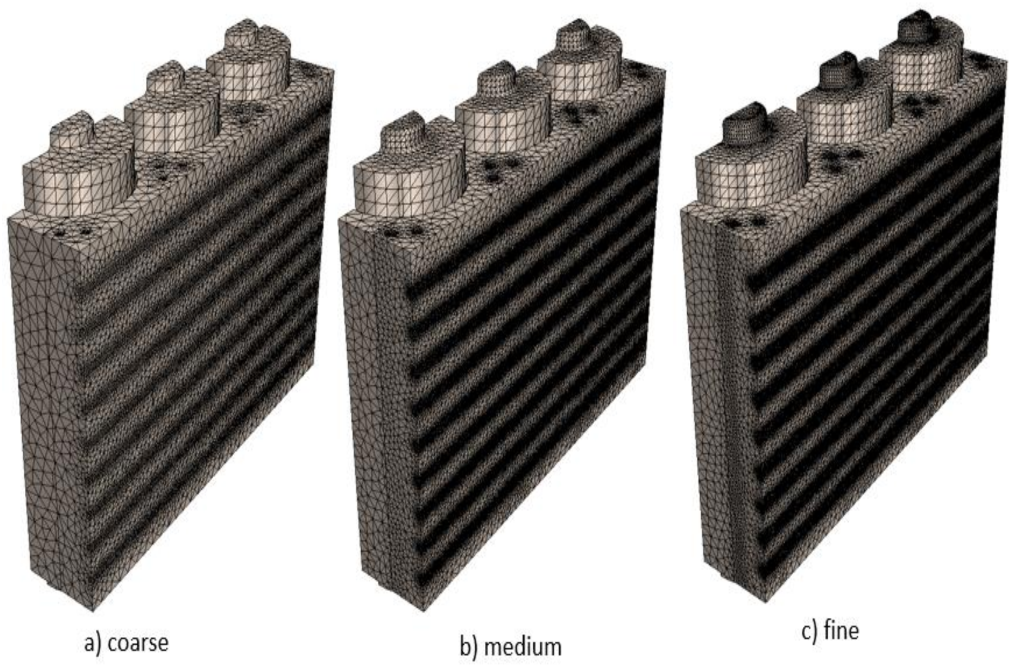


Figure 21 Coarse Mesh, Medium Mesh and Fine Mesh Scenes

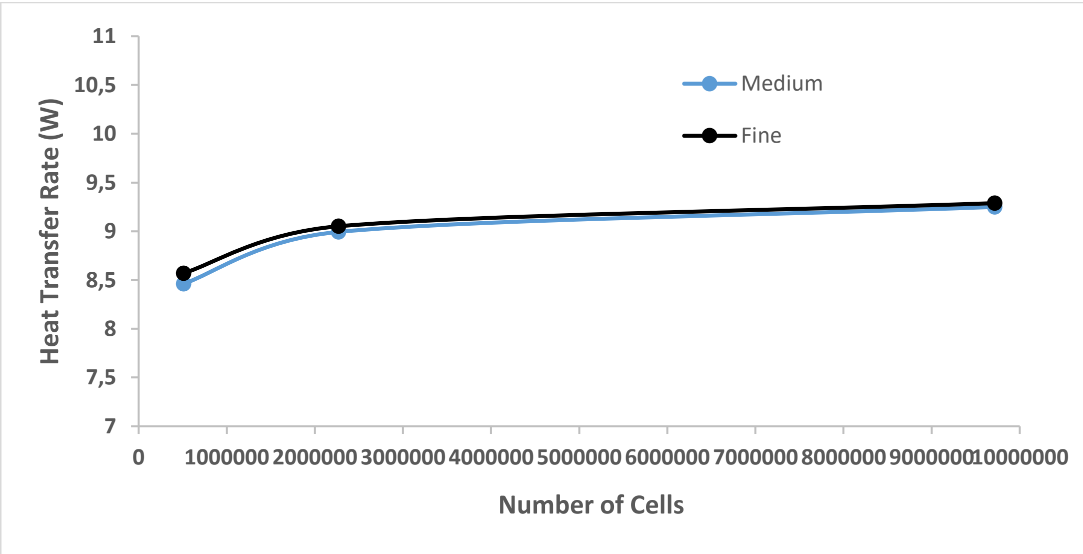
Table 7 Number of Grids

Coarse	Medium	Fine
509,698	2,269,546	9,716,803

Table 8 Mesh sizes used in geometry

	Coarse	**Medium**	**Fine**
Aluminum Block	14 mm	7.5 mm	4 mm
Cells	12.5 mm	5 mm	2 mm
Fluid	2 mm	1.5 mm	1.25 mm

Heat transfer rate and absolute errors among different mesh numbers are investigated and these studies are shown in Figure 22. According to the Figure 23, fine and medium mesh are very close to each other and the absolute error only differs about 3-5% so considering easiness, time and cost, all analyses are done with medium mesh. Mesh independency are completed for 3C battery at 0.1 m/s of inlet water velocity. As seen from Figure 23, after catching uniform increase temperature trend - 600 seconds later than starting from analysis -, error calculation has been made based on heat transfer rate change with time.



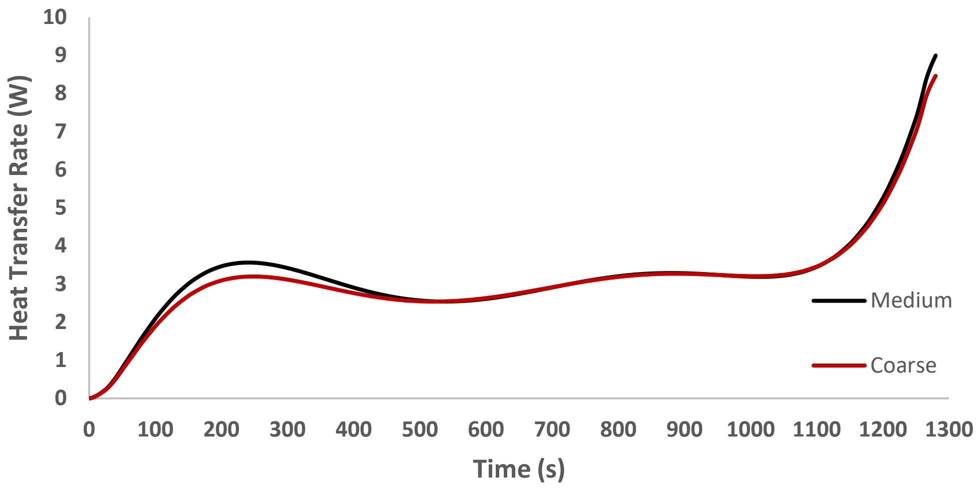


Figure 22 Heat transfer rate change at the end of 1300sec

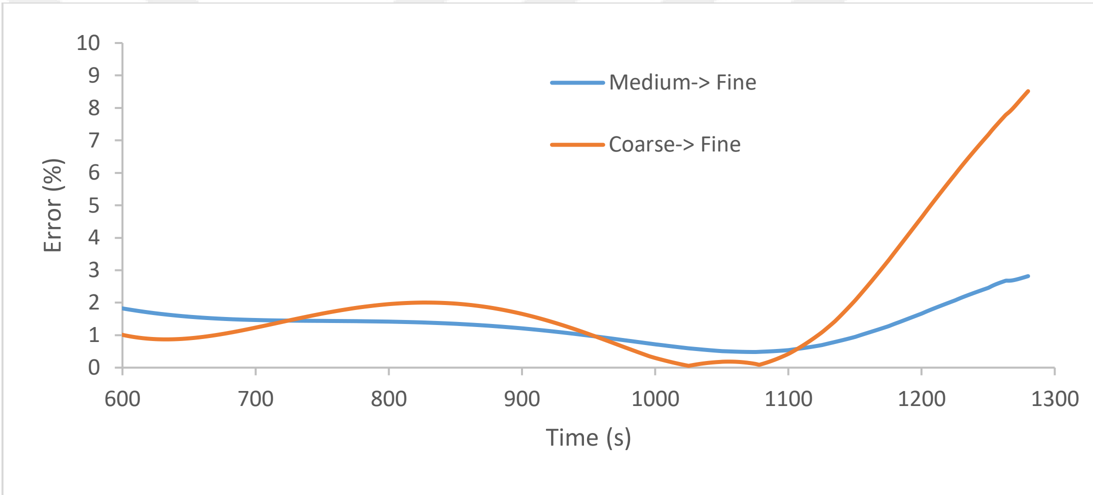


Figure 23 Mesh independency study based on error on heat transfer rate change

As a summary of mesh study, there different mesh has been analyzed under same conditions and their results have been compared with each other with their error percentage.

3.4.3 Convergence Study

As seen Figure 24 below, convergence of numerical analysis has been shown on a graph. In the line of expectancy of realizing correct numerical analysis values have been reduced around or below than $\mathbf{10^{-6}}$. *k*-epsilon model has been selected, which was originally derived by attempting to solve for epsilon using the Navier-Stokes equation.

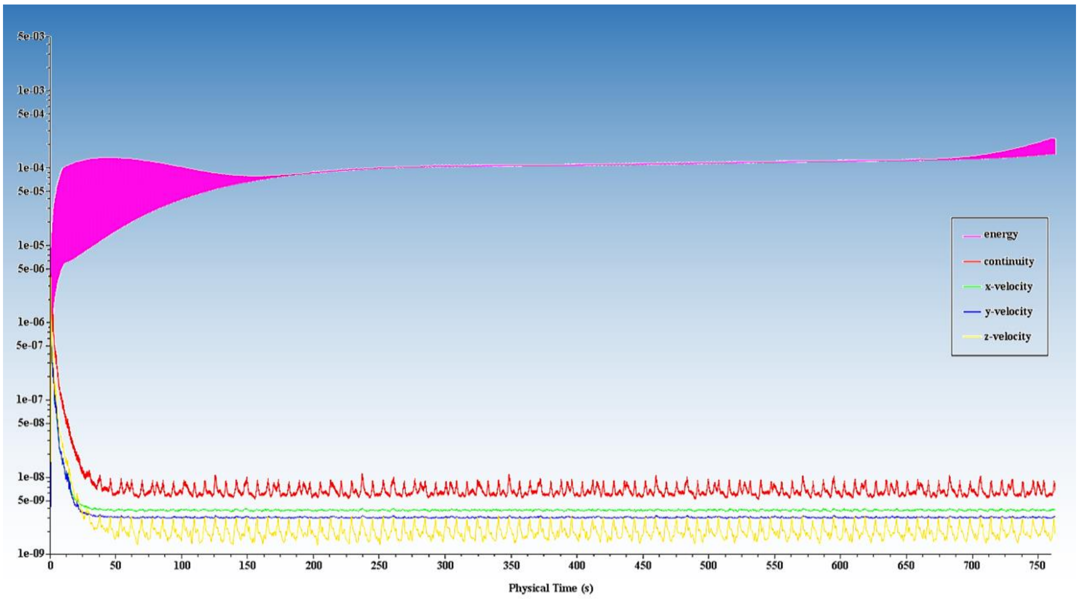


Figure 24 Converge study of numerical analysis

3.5. Experimental Study

In order to confirm numerical analysis, the experiment of temperature effect on a single battery was done and compared with the numerical results. During the analysis, similar results from researches have been taken as reference for the experimental study. For studying thermal performance of liquid cooled thermal management system for cylindrical lithium-ion battery module, [45] Rao et all. have tested a single battery instead of whole cooling system and then correlated their numerical analysis results with experimental results. In the light of the above study, experimentation has been done according to 3C discharge rate as a reference and process has ended when the voltage reduced to 2.1 – 2V.

Details of the experimental work is introduced the following parts, and result have been compared with numerical analysis in the next chapter.

3.5.1. Experimental Setup

To satisfy technical requirements of expectations of the experiment, all equipment have been selected properly and all measurement devices are calibrated.

As seen from the pictures of the setup in Figure 25, there are four main elements as; battery (1), Imax Balance Charger/Discharger (2), ZBL (smart circuit that helps to store heat and monitored) with dummy load (3) and infrared thermometer (4). Details and their working principles are given within next paragraphs.

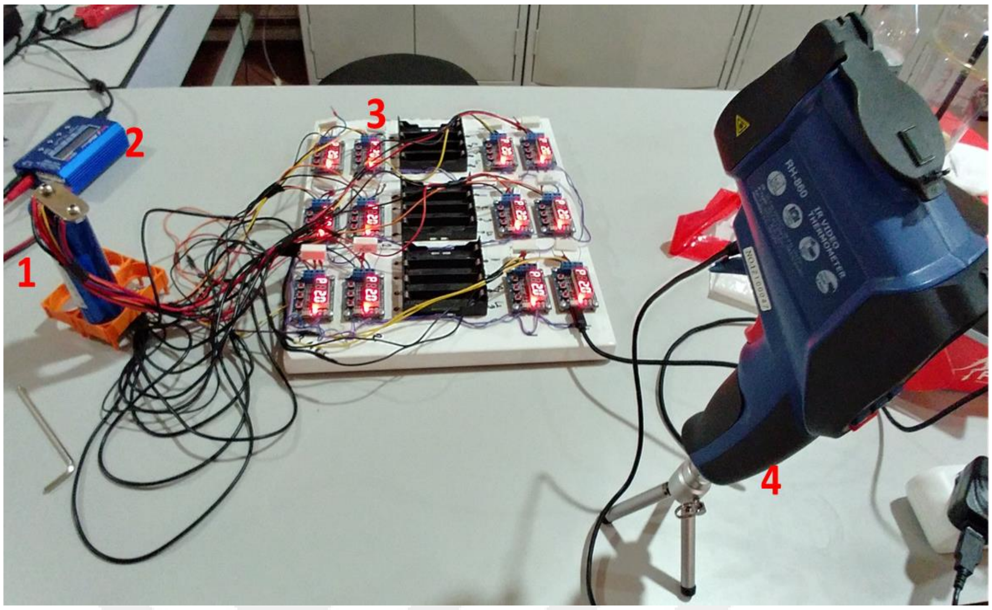


Figure 25 Experimental setup of the study

The battery module consists of a battery, plastic battery seat, battery screws and connection elements. Which can be used for whole serial or parallel battery pack connections.

The device has been shown with number 2 is called as Imax device which is the device to measure inner resistance of the battery and to charge or discharge the battery at different charge rates.

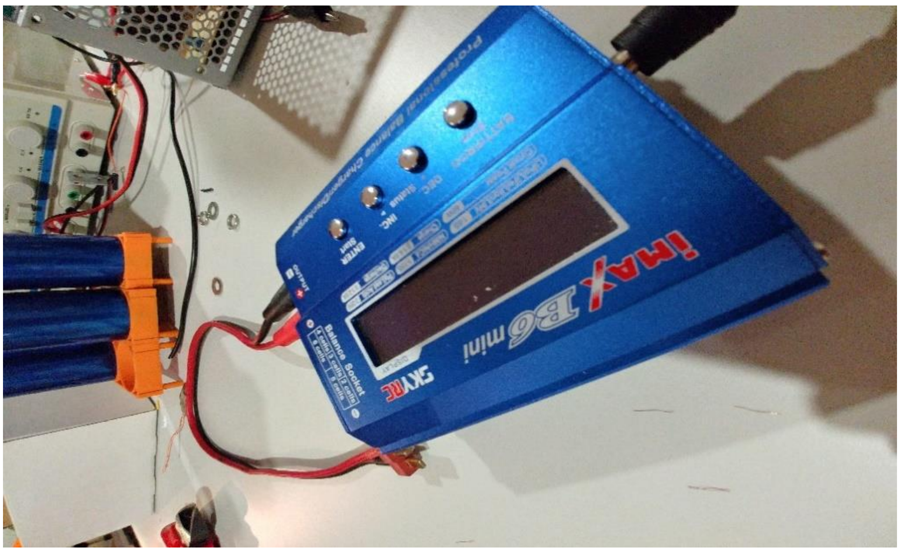


Figure 26 The Imax Balance Charger/Discharger

Number 3 identifies the dummy load board, which includes 12 number ZBL connections. There is a small smart chip which also includes negative and positive connections, an indicator and a resistance to storage heat during the discharge. As seen from Figure 27, indicator is small led screen and the rectangular prismatic shape is the 5-ohm resistance. Colorful cables have been connected to positive pole of the board and black one has been connected to negative pole of the board. There is also a detail of smart chip which can be seen in Figure 28 below.

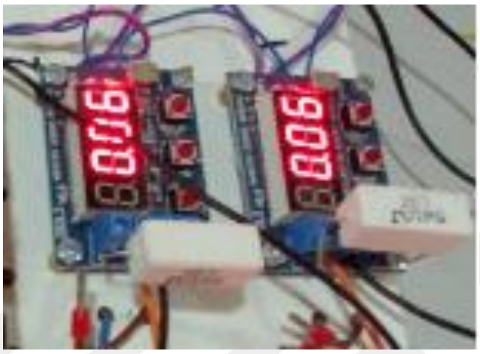


Figure 27 Details of ZBL board

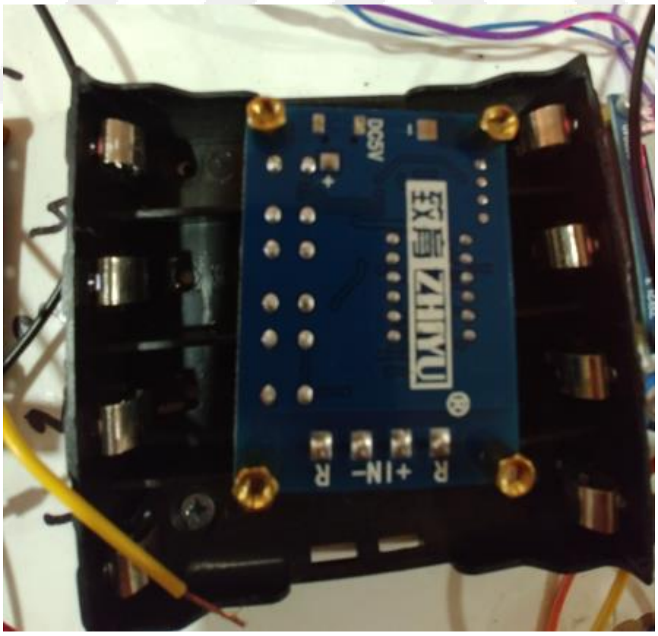


Figure 28 Details of mini board one of the 12 mini boards

Number 4 is the device used to measure and record the temperature of the battery during charge and discharge. Device records the temperature of battery each second. Thanks to infrared measurement method, temperature has been measured 13 cm away from the battery, that means result is reliable according to data sheet of the device in the line of its capability. The properties of the infrared thermometer can be seen in Figure 30 below.

Figure 29 Usage of infrared thermometer

Table 8 Technical measurement capability of infrared thermometer

Specifications	**Values**
IR Temperature Range	-50 to 2200℃
Resolution	0.1℃
Basic Accuracy	±1.0% of reading
Optical Resolution	50:1
Response Time	Less than 150ms

3.5.2. Experimental Procedure

The process starts with charging the battery with Imax device independently. After charging the battery, its inner resistance is measured to check if the assumption is correct, the assumption is unless its own inner resistance doesn't reach catalog value, it doesn't storage enough energy as used in the numeric solution. Then ZBL board is connected serially and parallel in order to create the dummy load. Dummy load is important to storage electricity and current as heat source and to take all energy of battery equally. In order to active system power input, to provide necessary demand of energy to start ZBL circuits – it includes indicator that shows the temperature value that is the source of consumption how much energy need for each ZBL. USB Type-C connection is connected, and it satisfies the required energy to provide to take current from the battery. While connection of each mini ZBLs, instead of using a common cable, separate cables are connected to battery in order not to affect temperature on the battery. Because, while voltage is dropping, common cable can increase battery temperature and could cause convective heat transfer from cable to battery.

The main purpose of using ZBL is to protect voltage of battery above 2 – 2.1V, to take stable values from experiment it is a necessary step that was applied in many reference studies. To control voltage, indicators that connected to each ZBLs were used. When the battery voltage reduces to 2V, all indicator of ZBLs gave a signal to warn about battery potential. Then dummy load cuts off the current about the lowest potential of battery. With the cut off, the maximum temperature of battery can be observed.

During the measurement stage, infrared thermometer is set 10-13 cm away from the battery, and the camera takes temperature values from two different positions. While logging the data, average values is recorded. The measurement was realized in each second, and 1854 values have been recorded with infrared measurement device.

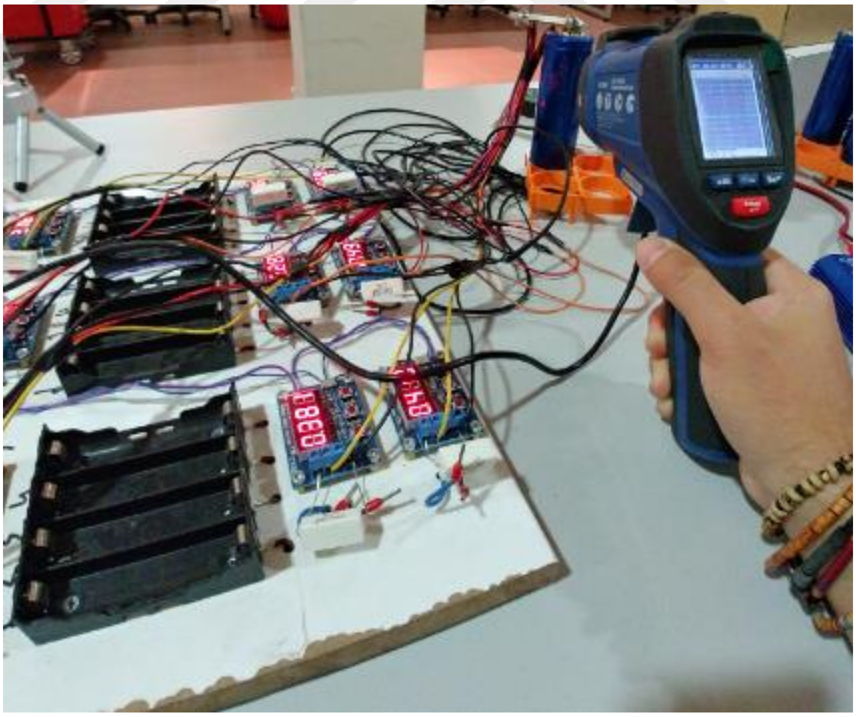


Figure 30 Measurement method of infrared thermometer

During the measurements, infrared thermometer is set 10-13 cm away from the battery, and the camera takes temperature values from two different positions. While logging the data, average values is recorded. The measurement was realized in each second, and 1854 values have been recorded with infrared measurement device.

3.6. Result of Experimentation and Validation of the computational results for thermal behavior of Li-ion battery

During the experimentation with 3C discharge rate, data have been collected for each second, for 1854 seconds, 1854 temperature value have been recorded and the temperature graph has been created as seen from Figure31.

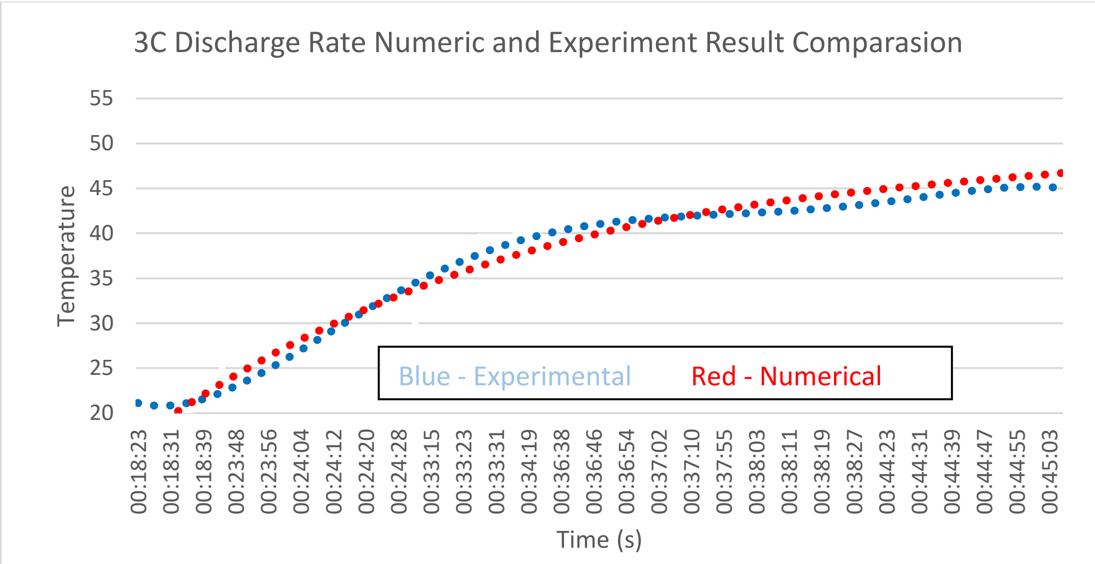


Figure 31 Validation of experimental and numerical results using with temperature increase under 3C discharge rate for a single battery

To confirm numeric results that will be presented within next section, experimental conditions have been applied and analyzed in simulation. For example, in many articles and our numerical study, room temperature has been assumed as 22°C, but the environment where experiment realized was under 18°C with 3C discharge rate and without any flow speed. Therefore, in order to confirm numerical results, analyzed has been tried under same temperature. Trend of temperature increase with discharging are almost same between numeric and experimental results.

This confirmation method with numeric and experimental result has been used in Rao’s study [46] and it was taken as main way for the our study to measure our capability of BTMS under same circumstances.

Percentage error between experimental and numerical result has been found as %7 in our study.

CHAPTER 4

RESULTS

4.1. Results of Numerical Analysis

In this section, details of computational analysis are given at three different main investigations. Firstly, temperature changes have been analyzed under different discharge rates for both vertical and horizontal cooling methodologies. Secondly, temperature distributions have been illustrated for different flow rates of cooling. Finally, performance has been compared between horizontal and vertical cooling.

Cooling performance of vertical and horizontal cooling methodologies are illustrated in the figures below for different flow rates under same discharge rates. On the figures, besides the geometry, batteries, battery block and the cooling channels can be seen.

Details about simulations of the battery pack including geometry, discharge rate, flow rate, and figure numbers of the temperature contours can be seen in Table 10.

Table 9 Simulation details of the computational analysis

Simulation #	Geometry	Discharge Rate	Flow Rate m/s	Figure Number
1	Horizontal	1C	0,05	32
2	Vertical	1C	0,05	33
3	Horizontal	1C	0,5	34
4	Vertical	1C	0,5	35
5	Vertical vs Horizontal	1C	0,05	36
6	Horizontal	3C	0,05	37
7	Vertical	3C	0,05	38

8	Horizontal	3C	0,1	39
9	Vertical	3C	0,1	40
10	Horizontal	3C	0,2	41
11	Vertical	3C	0,2	42
12	Horizontal	3C	0,4	43
13	Vertical	3C	0,4	44
14	Vertical vs Horizontal	3C	0,05	45
15	Vertical vs Horizontal (Pack)	3C	0,05	46
16	Vertical vs Horizontal	3C	0,05	47
17	Vertical vs Horizontal	5C	0,4	48

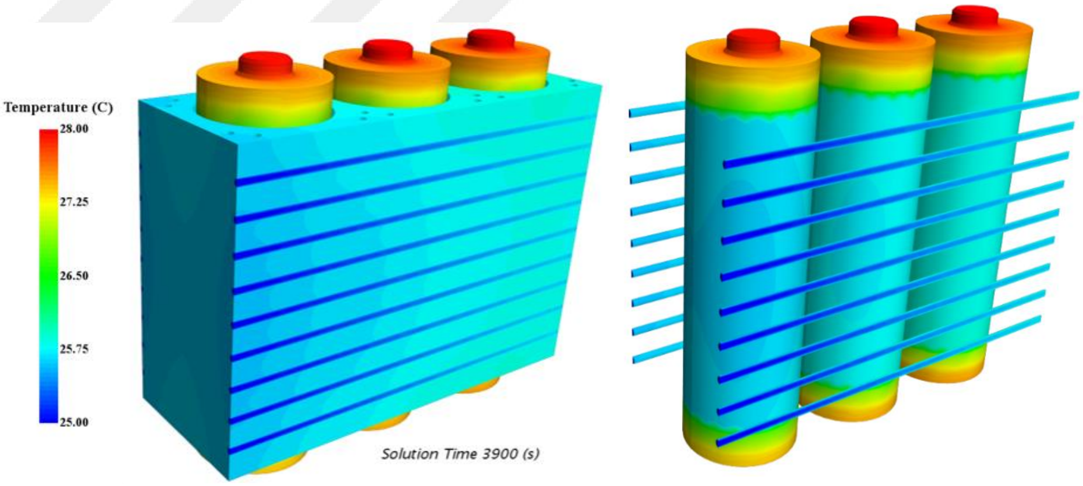


Figure 32 Cooling Performance of Horizontal Cooling at 0.05 m/s flow velocity under 1C Discharge Rate

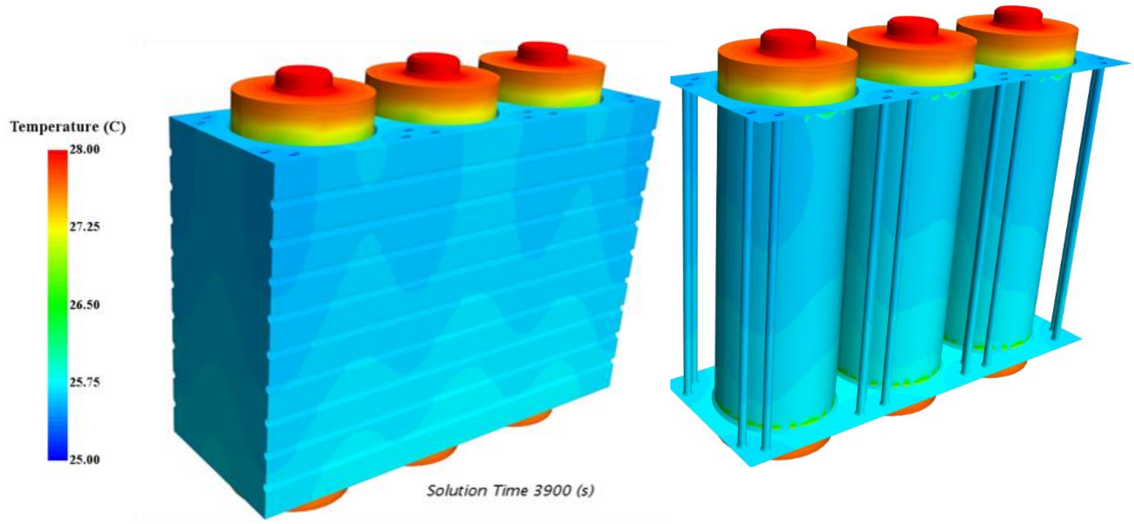


Figure 33 Cooling Performance of Vertical Cooling at 0.05 m/s velocity under 1C Discharge Rate

It could be noticed from above figures that thermal performance of horizontal cooling is a little bit effective than vertical cooling with low flow rate and at low discharge rates. Temperature differences through the battery is also quite similar with 0.05 m/s flow sped.

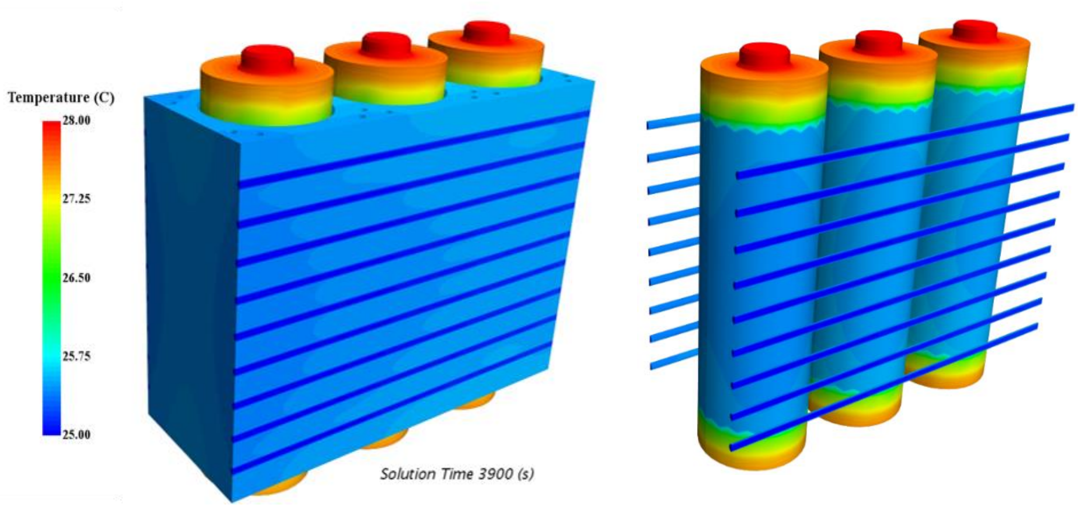


Figure 34 Cooling Performance of Horizontal Cooling at 0.5 m/s velocity under 1C Discharge Rate

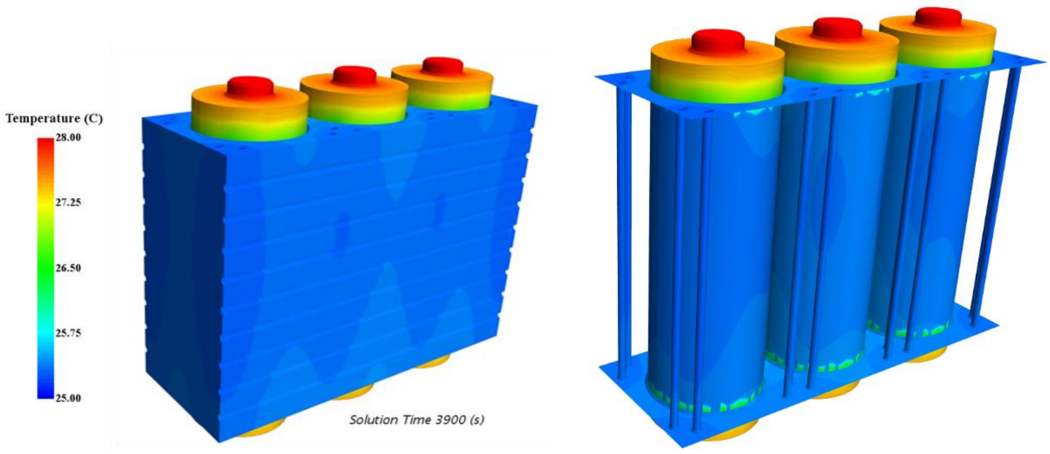


Figure 35 Cooling Performance of Vertical Cooling at 0.5 m/s flow velocity under 1C Discharge Rate

Cooling results of both vertical and horizontal cooling with 0.5 m/s water inlet velocity have been shown Figures (34 and 35 respectively) under 1C discharge rate. Despite of low discharge rate, flow rate is meeting cooling requirement. As seen from figures, cooling performance could be accepted as adequate.

As seen from figure above, results of both horizontal and vertical cooling under 1C discharge rate with 0,5m/s aren't comparable with each other. In both cases, it could be assumed that satisfying cooling could be provided.

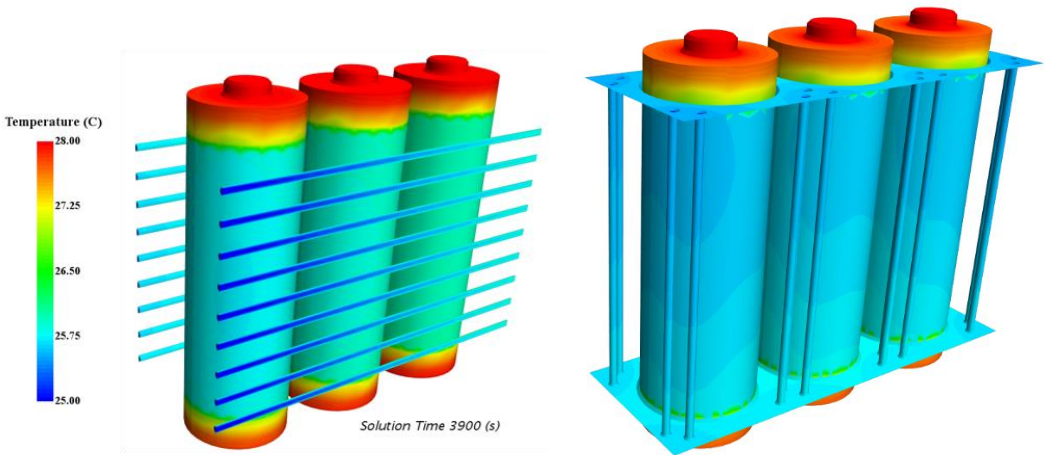


Figure 36 Cooling performance comparison of horizontal (left) vs vertical (right) channels of 1C Battery at 0.05m/s flow velocity

After testing and observing the temperature distributions for effects of cooling performance under 1C discharge rate, analysis have been shaped to be realized according to 3C discharge rate with different flowrates. Comparison of performance difference and are shown on figures below. First analysis of 3C discharge rate is realized as it is completed in 1C discharge rate with same flowrate.

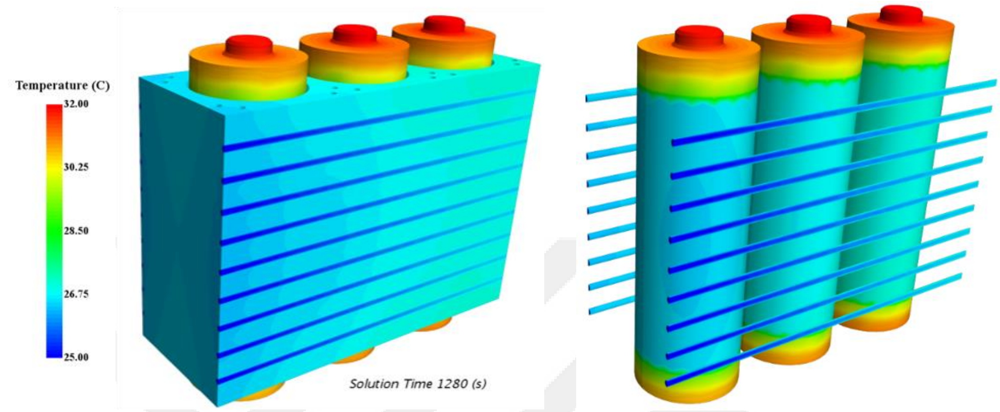


Figure 37 Cooling performance of horizontal channels of Battery under 3C Discharge Rate at 0.05m/s flow velocity

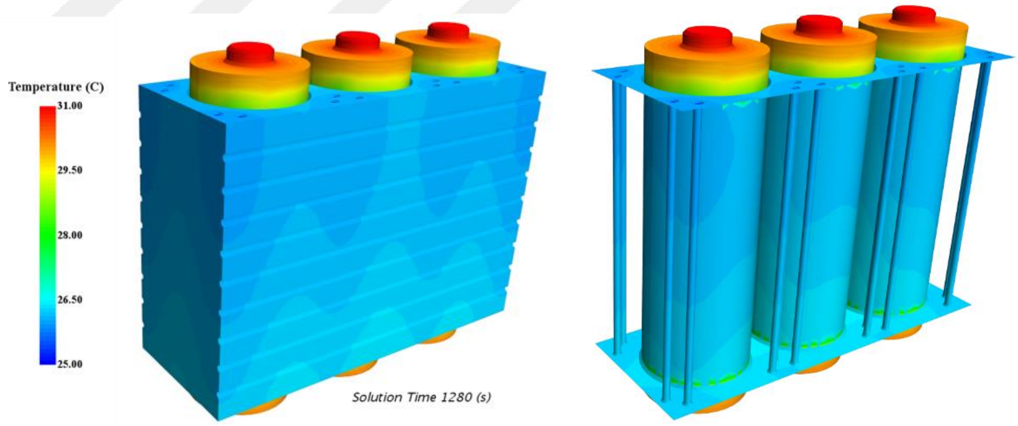


Figure 38 Cooling performance of vertical channels of Battery under 3C Discharge Rate at 0.05m/s flow velocity

As seen from Figure 37 and Figure 38, but with increasing discharge rate, vertical channel cooling gives a positive signal when compared.

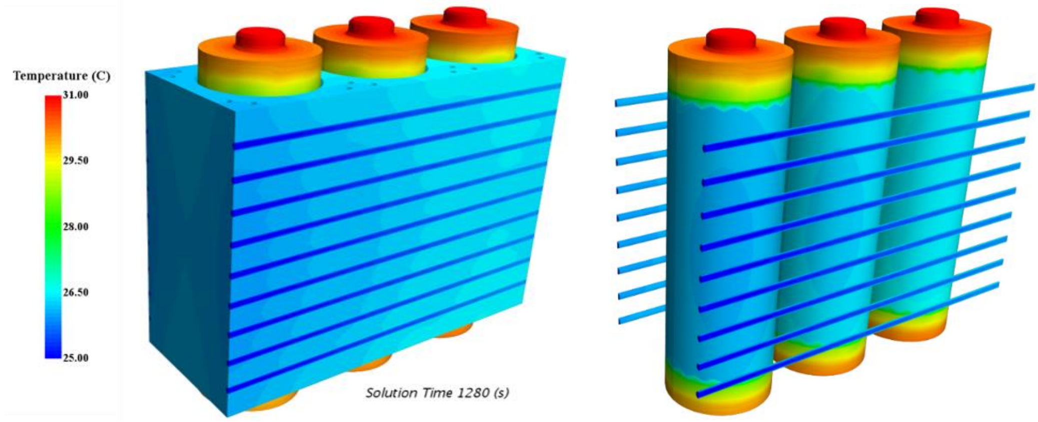


Figure 39 Cooling performance of horizontal channels of Battery under 3C Discharge Rate at 0.1m/s flow velocity

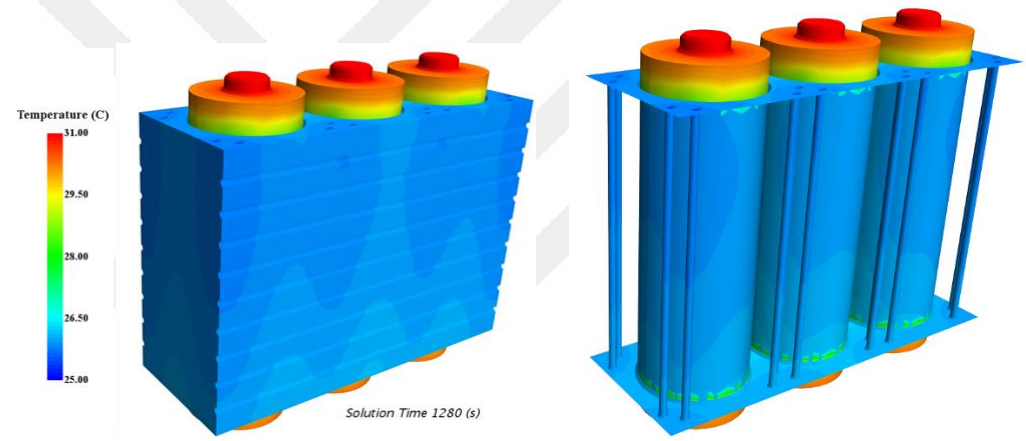


Figure 40 Cooling performance of vertical channels of 3C Battery at 0.1m/s flow velocity

As seen from Figure 41 and Figure 40, both of cooling methods almost affect same performance on the battery, vertical channel cooling gives more positive signal than both previous comparison and horizontal cooling. Also when compared with lower rates of water, increasing flow rate increases the cooling performance as can be predicted.

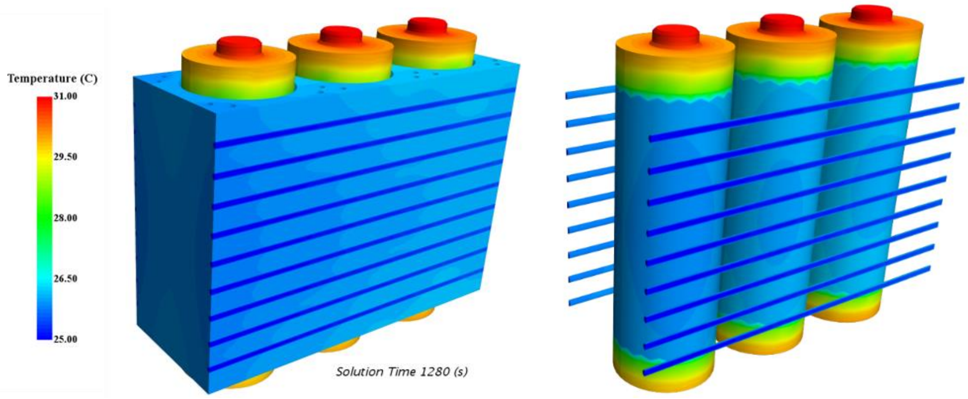


Figure 41 Cooling performance of horizontal channels of 3C Battery at 0.2m/s flow velocity

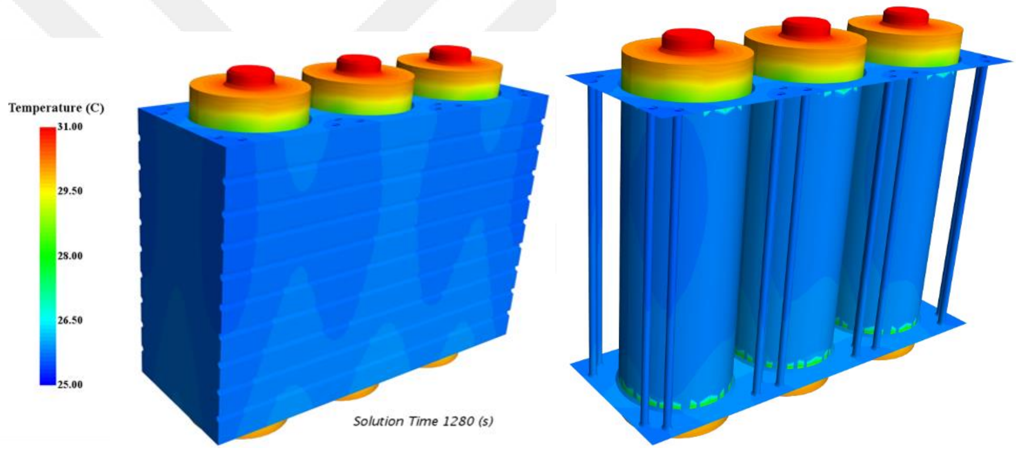


Figure 42 Cooling performance of vertical channels of 3C Battery at 0.2m/s flow velocity

As seen from Figure 41 and Figure 42, both of cooling methods almost affect same performance on the battery, vertical channel cooling gives better results than horizontal cooling.

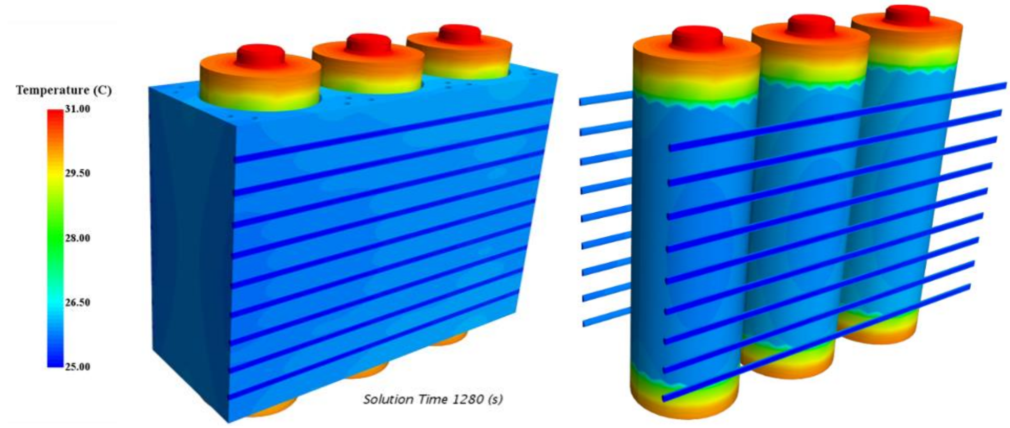


Figure 43 Cooling performance of horizontal channels of 3C Battery at 0.4m/s flow velocity

Unlike low flow rate of cooling in channels, higher flow rates show quite comparable results between vertical and horizontal channel cooling. Illustration could be seen in Figure 43 and Figure 44 below. Battery module comparison also has been illustrated in Figure 44. Red regions (above than 31°C) only occurs where ionization starts at polar regions.

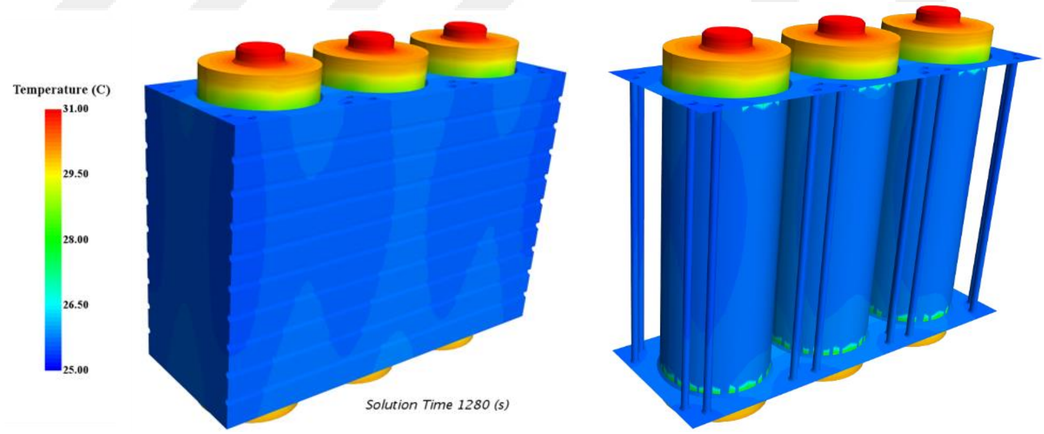


Figure 44 Cooling performance of vertical channels of 3C Battery at 0.4m/s flow velocity

As seen above figures, temperature distribution of battery and its modules at 0.4 m/s and at 3C discharge rate is quite similar.

With low flow velocity and flow rate, vertical channel cooling shows more effective results than horizontal cooling. Especially, Figure40 below shows temperature differences at the same regions which are polar regions distinctly.

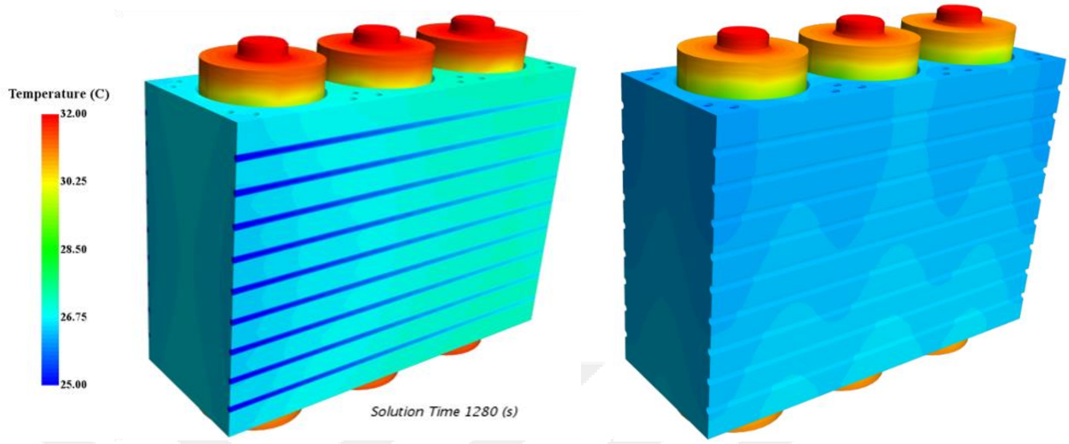


Figure 45 Cooling performance comparison of vertical and horizontal channels of battery pack under 3C discharge rate at 0.05m/s flow velocity

It is worth to reveal that cooling effect of changing velocity under the same discharge rate could be taken as a reference point in order to detect best cooling strategy. In this context, Figure 46 and Figure 47 give us a point for comparison that 0.4m/s flow velocity is more effective than 0.1m/s. Of course, as mentioned above in a few cases, vertical channel cooling is much more effective than horizontal cooling.

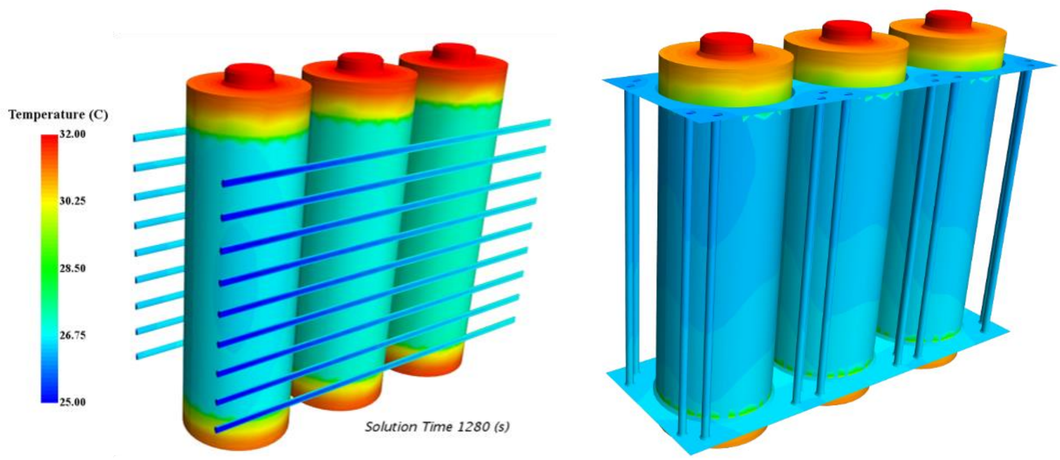


Figure 46 Cooling performance comparison Horizontal (left) vs Vertical (right) Channels of 3C Battery at 0.05m/s flow velocity

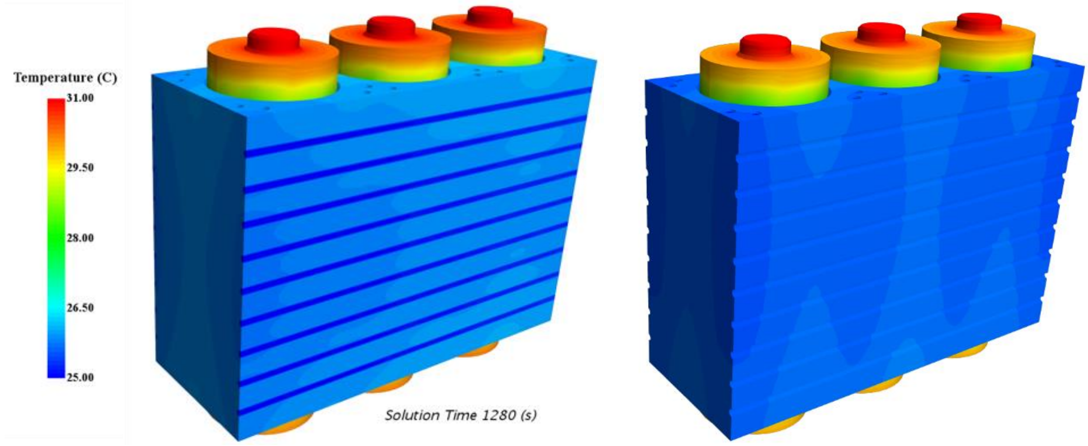


Figure 47 Cooling performance comparison of Horizontal (left) vs Vertical (right) Channels battery pack of 3C Battery at 0.4m/s flow velocity

Battery module temperature of both cooling strategies are almost same. There is an example that reveals this assumption in Figure 47.

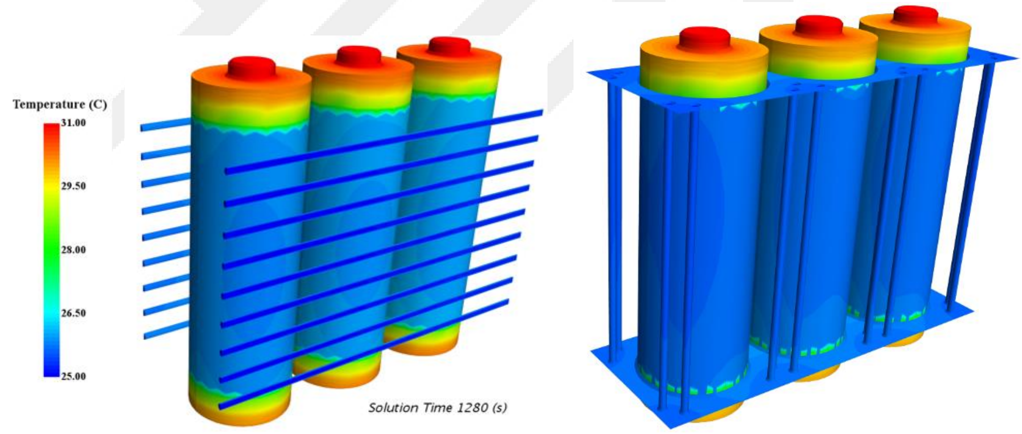


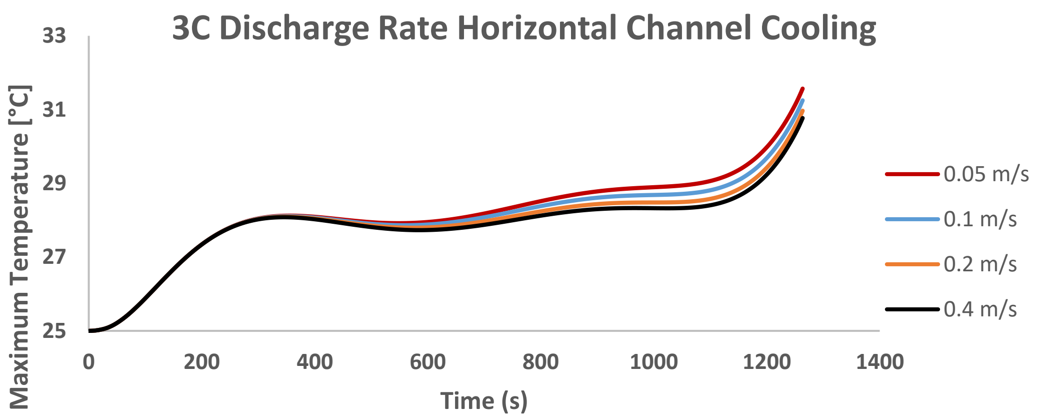
Figure 48 Cooling performance comparison of Horizontal (left) vs Vertical (right) Channels of 5C Battery at 0.4m/s flow velocity

If it must be shown with graphics of performance accordingly changing flow velocity, some figures have been illustrated in blow under the same discharge rates. Firstly, details of horizontal cooling, then details of vertical cooling have been shown on below figures. After all, the comparison of each methods was compared according to same flow velocity under the same discharge rate with each other so that decision of the best method could be proven.

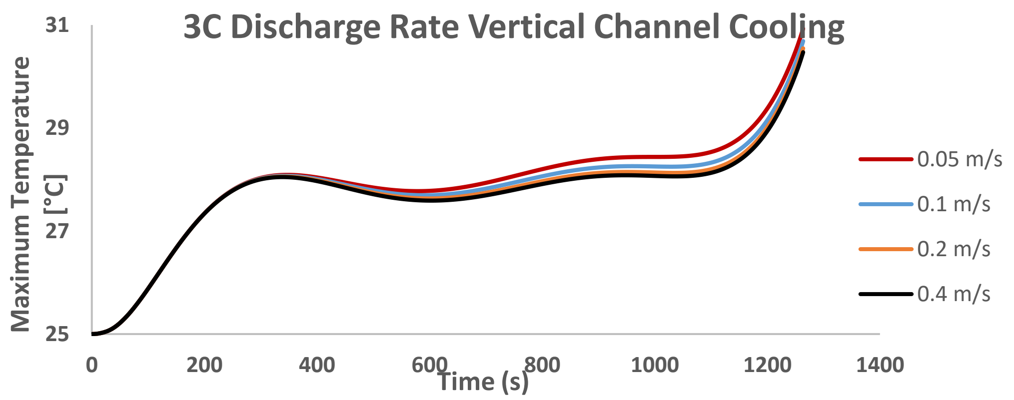
Due to small effect of differences of low discharge rate 1C, illustrations have been started to show with flow velocity effect of 3C discharge rates and 5C discharge rates. Therefore, as made in many studies, it was taken as reference to compare results of cooling methods under high discharge rates.

After showing illustration of battery modules under different discharge rates and different cooling speeds, graphically results could be seen in figures below to reveal differences more clearly.

In Figure 49(a), 3D discharge rate horizontal cooling for different flow velocities can be seen. In Figure 40(b), 3D discharge rate vertical cooling for different flow velocities can be found.



(a)



(b)

Figure 49 Temperature change graph of both horizontal (a) and vertical (b) cooling methods under 3C discharge rate with various flow velocity

As seen from Figure 54 vertical channel cooling shows much more effective results than horizontal cooling under same circumstances. While the temperature is exceeding 31.6℃ after 1300s starting with 22℃ in horizontal channel cooling, it could be held under 30.9℃ in vertical cooling under same circumstances.

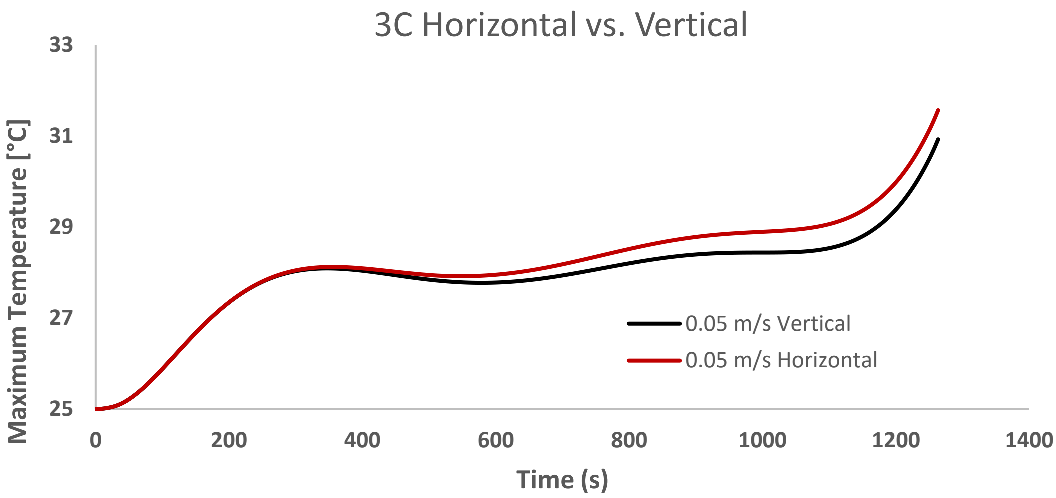


Figure 50 Temperature change comparison graph between horizontal and vertical channel cooling methods under 3C discharge rate with the lowest flow velocities.

As mentioned in above paragraph Figure 50 compares the most efficient flow speeds of two methods. With this figure its is could be easily noticed that vertical cooling is more efficient that horizontal channel cooling.

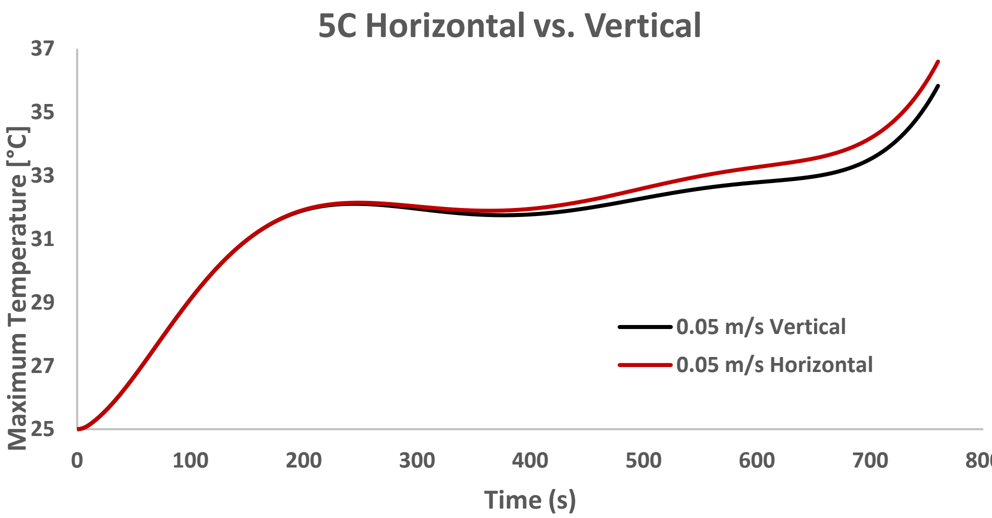
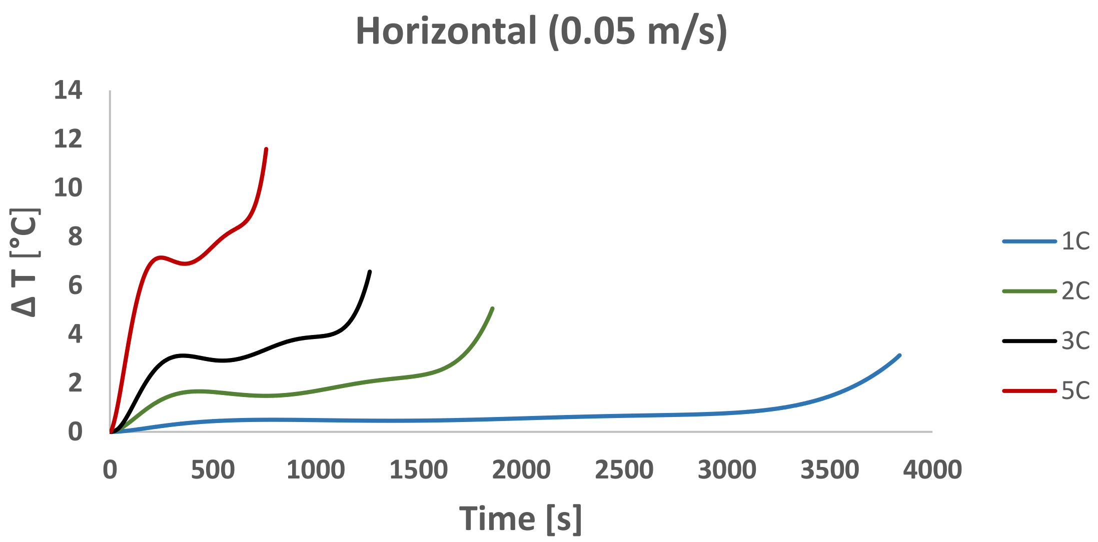
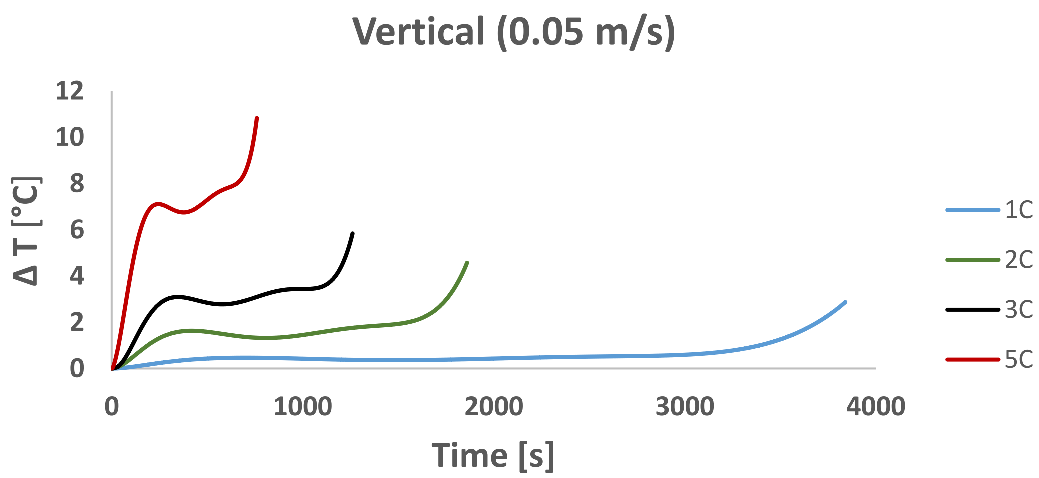


Figure 51 Temperature change comparison graph of between horizontal and vertical cooling channel methods under 5C discharge rate with the lowest flow velocity

Comparison methods of cooling methods under 3C discharge rate has been applied for 5C discharge rate under same flow velocity 0.05m/s. As shown in Figure51, vertical cooling is more effective than horizontal cooling under same circumstances. After 800 seconds later, the differences could exceed 2℃, so that It could create huge benefit for selecting BTMS.



(a)

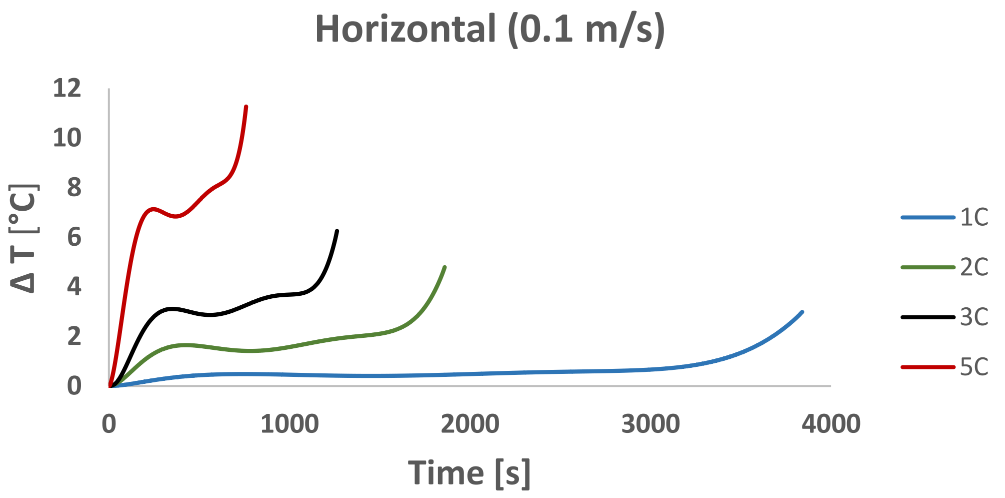


(b)

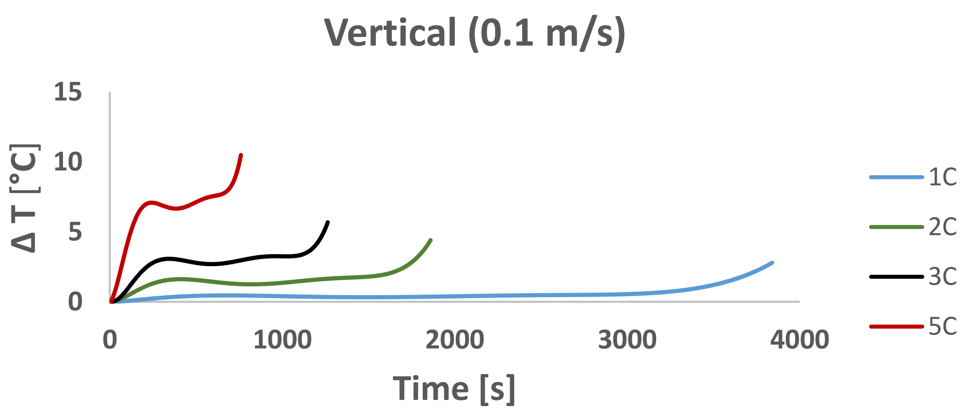
Figure 52 Temperature change graphs of flow velocity with 0.05m/s at (a) horizontal and (b) vertical cooling methods under various discharge rate with constant flow velocity

As seen as in previous comparisons, 0.05 m/s which is the lowest flow velocity that was tried among flow velocities gives the most efficient results in both vertical and horizontal cooling. Laminar cooling is the most efficient way for channel type BTMS for liquid cooling methods. To observe effect of the lowest flow velocity with various discharge rate, Figure52 was created.

Similar thermal performance behavior could be observed with 0.1 m/s flow velocity at various discharge rates. As seen from Figure53, temperature differences were illustrated with time.



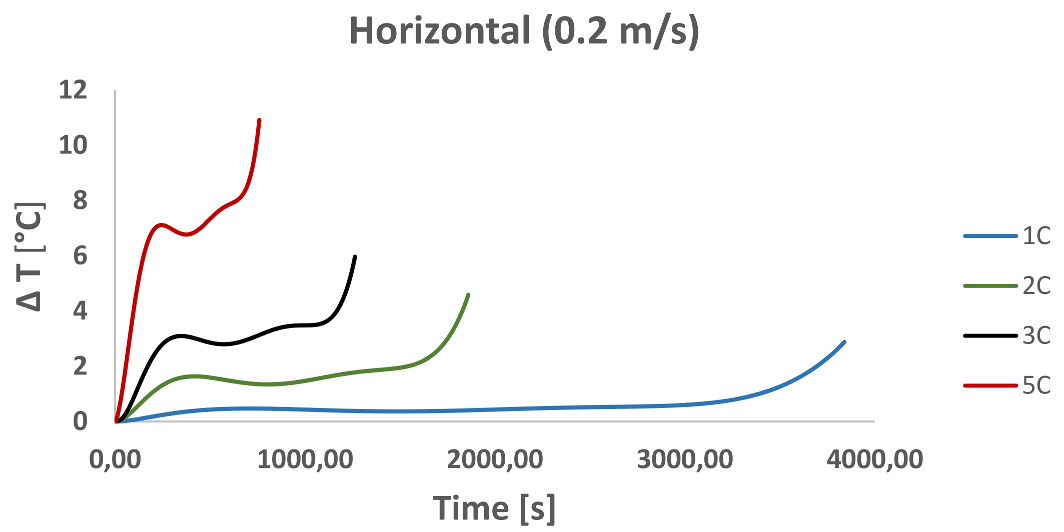
(a)



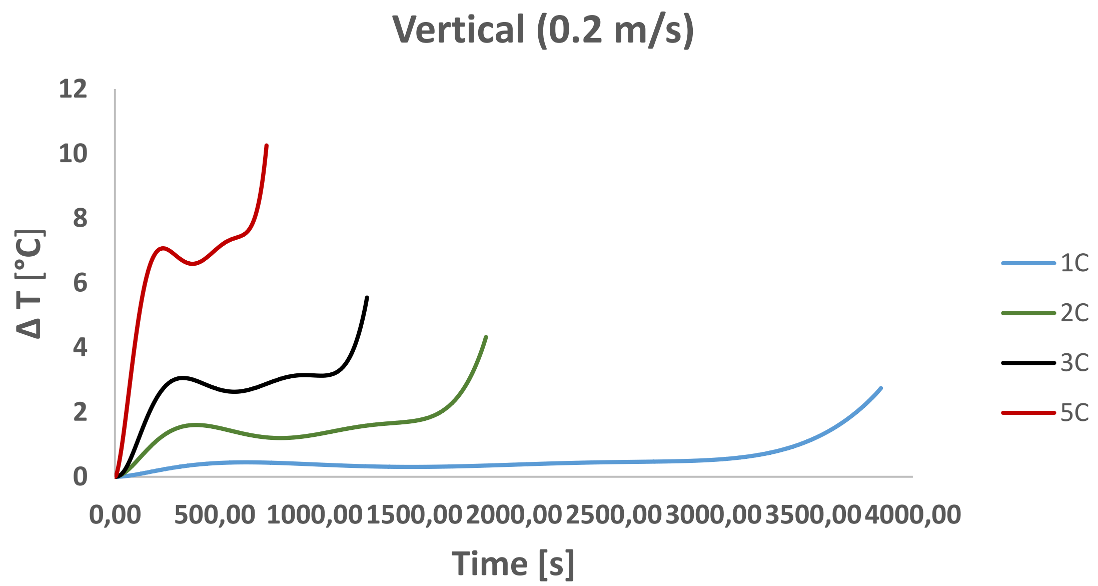
(b)

Figure 53 Absolute temperature change graphs of flow velocity with 0.1m/s at (a) horizontal and (b) vertical cooling methods under various discharge rate

Flow velocity of 0.2m/s and 0.4m/s have been also compared according to vertical and horizontal cooling channel in terms of temperature differences on the battery, Figure 54 and Figure 55 define these illustrations. It is obvious that vertical channel gives better results.

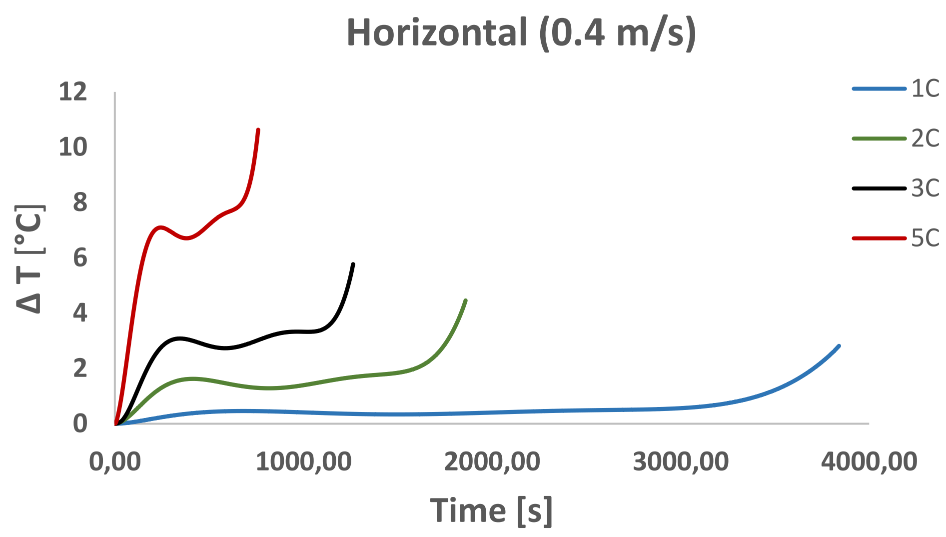


(a)

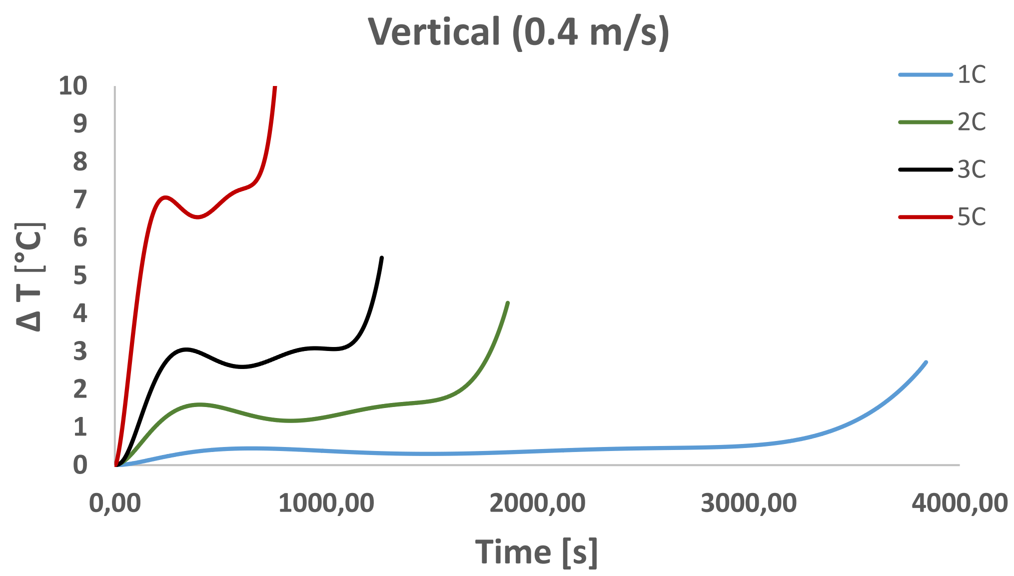


(b)

Figure 54 Absolute temperature change graphs of flow velocity with 0.2m/s at (a) horizontal and (b) vertical cooling methods under various discharge rate



(a)



(b)

Figure 55 Absolute temperature change graphs of flow velocity with 0.4m/s at (a) horizontal and (b) vertical cooling methods under various discharge rate

As a conclusion of numeric analysis, low discharge rate doesn't cause huge temperature differences comparing higher discharge, reasons of that has been explained in previous sections. In literature, 3C or 5C are the most compared discharge rates for BTMS. Therefore, in the thesis, 3C is the mainly focused discharge rate to obtain tangible results comparing with literature experiments.

In the line of defining discharge rate as 3C for both numerical and analytical study, results were collected under the same table. As seen from Table 11 below, both temperature and performance comparison have been listed according to changing flow velocity.

Table 10 Details of temperature change and performance comparison

Geometry	T°C max	Discharge	Flow Rate	Performance Comparison Between Horizontal and Vertical Channel
Horizontal	31,39	3C	0,05	
Vertical	30,93	3C	0,05	+ 7.3%
Horizontal	30,91	3C	0,1	
Vertical	30,60	3C	0,1	+ 3,5%
Horizontal	30,75	3C	0,2	
Vertical	30,45	3C	0,2	+ 3,5%
Horizontal	30,59	3C	0,4	
Vertical	30,2	3C	0,4	+ 4,5%

To illustrate performance effect of flow rate on a single battery, the lowest and the highest flow velocity were compared in the table below. For this comparison, vertical channel cooling, which gives better results than horizontal, has used as constant comparison parameter. With this approach, 0,4m/s flow velocity provide 8,9% more transferred heat advantageous over 0,05m/s under 3C discharge rate.

Table 22 Performance comparison of flow speed in vertical cooling

Geometry	T°C max	Discharge	Flow Rate m/s	Performance Comparison
Vertical	30,20	3C	0,4	+ 8,9%
Vertical	30,93	3C	0,05	

CHAPTER 5

DISCUSSION AND CONCLUSION

During the study, the main cooling method has been selected as liquid cooling in our BTMS since this is the most effective method used in industrial applications. Geometrical design, circulation flow rate and fluid type have been defined as direct parameters for BTMS performance improvement. Circulation flow rate effect on the performance hasn't been studied in any of Liquid BTMS in literature, design and circulation flow rate create differences between studies.

In this context, successful studies, those are most realist and close results to existing industrial applications, have been collected in the one roof. Those are Chen et all [19], Lan et al. [20], Zhang et al.[21], Tong et all [22], Jin et all [23], Jarett and Kim[24], Huo and Zhao [25], Yang et all [8]. Basically, all successful design uses aluminum storage device or transmitter in their studies, with low speed circulating flow.

As explained in previous sections, in this study thermal performance of liquid cooling based thermal management system for cylindrical lithium-ion battery module is studied and aluminum block with channel cooling is selected as the cooling geometry. Study of Rao et all [46] has been selected as guide for our study.

In the study, Rao has selected horizontal pipe, but both vertical and horizontal pipes were tested in our study in the same flow speed. The aluminum jacket size and structure are different than Rao. Rao has changed aluminum size besides flow speed to find the most appropriate one.

Among the study, after confirmation of thermal behavior over a single battery seen in Figure 31, numerical study has showed a way to choose the most optimal design of

BTMS. Different geometries and flow rates have been simulated using computational program as can be seen in Table 10. As mentioned before, Rao's study has been selected as closed approach to our study and the most efficient one between other liquid battery thermal management systems.

In the study, two different channel cooling methodologies have been tried for 3 serial connected battery and results of both directions have been compared under same conditions for different flow rates of cooling water. Battery module weight and power need of BTMS haven't been considered for our study.

When the results are considered, geometry of the block and the cooling channel orientation is found to have a bigger effect and cooling circulation speed has less effect on performance of BTMS.

Results have been shown on Table 11 and Table 12 with details, according to various flow speeds performance of cooling systems have been compared. As a summary, performance differences of horizontal or vertical effect with increasing flow speed is reducing. For example, performance differences of these two methods with flow speed 0,05m/s is + 7.3%. On the other hand, advantages of vertical cooling with 0,4m/s is + 4,5%. That means, vertical cooling provides great advantageous with low flow speed. It is obvious that temperature differences on the battery is decreasing with increasing flow speed in both methods. For example, at 4m/s flow speed, battery temperature differences are 12.2°C and 12.6°C respectively vertical and horizontal channel cooling methods.

To sum up, vertical channel cooling could be much more successful cooling method according to horizontal cooling due to their increased area of contact surfaces of a battery. With this study, vertical channel cooling will be the first tested type in between cooling jacket or aluminum block type studies.
In future studies, those could be completed; performance effect of pipe diameter change, pump performance with general energy consumption, product weight optimization and test module could be produced and compared as empirically.

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