REPUBLIC OF TURKEY
ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY

INSTITUTE OF GRADUATE SCHOOL
DEPARTMENT OF MECHANICAL ENGINEERING

ANALYSIS OF BATTERY THERMAL MANAGEMENT SYSTEM IN ELECTRIC VEHICLES

GÖZDE EKMEKÇİ GÜÇLÜTEN
MASTER OF SCIENCE

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ASSOC. PROF. DR. GÖKHAN TÜCCAR

ADANA 2021

I hereby declare that all information in this thesis has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all information that is not original to this work.

[Signature]

Gözde EKMEKÇİ GÜÇLÜTEN

ABSTRACT

ANALYSIS OF BATTERY THERMAL MANAGEMENT SYSTEM IN ELECTRIC VEHICLES

Gözde EKMEKÇİ GÜÇLÜTEN
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With the rapid depletion of fossil fuels and the widespread use of the concept of clean energy, electric vehicles are replacing vehicles with internal combustion engines. Research on electric vehicles also includes alternatives to internal combustion engines in terms of price and reliability. States have started to take concrete steps on clean energy by changing their energy policies. In this context, they are making plans to limit the use of internal combustion vehicles and to terminate them completely in the near future. There are problems that need to be overcome in order for electric vehicles to reach the desired level. These problems stand out as low range and high battery cost. The most important parameter affecting the range and preferability of electric vehicles is battery technology. It is an inevitable fact that organizations that launch cost-effective and long-lasting battery systems will be in a strong position to dominate the automotive industry of the future. One of the biggest concerns in battery systems developed for electric vehicles is heat management in batteries. In particular, the temperature in the cells of lithium-ion (li-ion) batteries allows a limited degree of variation (°C) within the entire battery pack. Overheating and uneven temperature distribution cause rapid cell failure and shortened battery cycle life. In addition, in these cases, as the temperature rises uncontrollably, catastrophic damage to the battery may cause fire and explosion. The solution of these problems is directly proportional to the developments in battery technologies. The range of electric vehicles is directly related to the battery capacities, and it is desirable for the batteries to have high power density, high energy density, fast charge-discharge and long life. For all these reasons, electric vehicle battery packs include comprehensive cooling systems to remove heat from the battery systems and maintain an even temperature throughout the battery pack/module/cell. Therefore, today's electric vehicle research and development studies focused

on this issue. In this study, battery systems of electric vehicles are parametrically designed with 3D solid modeling program according to super ellipse geometry and thermal management of battery systems is realized. Heat management studies are done in ANSYS CFX. The effect of different determined parameters on the battery cell temperature is investigated. With MATLAB, D-Optimal experimental design is created with different parameters determined. Again, in MATLAB, a two-alternative optimization study is carried out as constraint function local optimization and genetic algorithm optimization. The obtained optimum values and the maximum temperature are reanalyzed and verified in CFX. As a result of the conducted analyzes and optimization, the effect of different parameters and geometries on thermal performance is investigated.

Keywords: electric vehicles, thermal management, super ellipse, CFX, MATLAB, experiment design, optimization

ÖZET

ELEKTRİKLİ ARAÇLARDA BATARYA ISIL YÖNETİM SİSTEMİ ANALİZİ

Gözde EKMEKÇİ GÜÇLÜTEN
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Danışman: Doç. Dr. Gökhan TÜCCAR
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Fosil yakıtların hızla tükenmesi ve temiz enerji kavramının yaygın olarak kullanılmaya başlanması ile birlikte elektrikli araçlar içten yanmalı motora sahip araçların yerini almaktadır. Elektrikli araçlar üzerine yapılan araştırmalar, fiyat ve güvenilirlik açısından içten yanmalı motorlara alternatif de içermektedir. Devletler enerji politikalarını değiştirerek temiz enerji üzerine somut adımlar atmaya başladılar. Bu kapsamda içten yanmalı araçların kullanımını sınırlandırma, yakın gelecekte ise tamamen sonlandırma planları yapmaktadırlar. Elektrikli araçların istenilen seviyeye gelebilmesi için aşması gereken sorunlar vardır. Bu sorunlar az menzil ve yüksek batarya maliyeti olarak öne çıkmaktadır. Elektrikli araçların menzillerini ve tercih edilebilirliklerini etkileyen en önemli parametre batarya teknolojisidir. Uygun maliyetli ve uzun ömürlü akü sistemlerini piyasaya süren kuruluşların, geleceğin otomotiv endüstrisine hakim olmak için güçlü bir konumda olacağı kaçınılmaz bir gerçektir. Elektrikli araçlar için geliştirilen batarya sistemlerindeki en büyük endişelerden biri ise bataryalardaki ısı yönetimidir. Özellikle, lityum iyon (li-iyon) pillerin hücrelerindeki sıcaklık, tüm pil paketi içinde sınırlı bir değişiklik derecesine (°C) izin verir. Aşırı ısınma ve dengesiz sıcaklık dağılımı, hızlı hücre arızasına ve pil çevrim ömrünün kısalmasına neden olur. Ayrıca bu durumlarda sıcaklık kontrolsüz bir şekilde arttığı için bataryada oluşabilecek feci hasarlar yangın ve patlamaya neden olabilir. Bu sorunların çözümü batarya teknolojilerindeki gelişmelerle doğru orantılıdır. Elektrikli araçların menzilleri batarya kapasiteleri ile doğrudan ilişkili olup, bataryaların yüksek güç yoğunluğuna, yüksek enerji yoğunluğuna sahip olması, hızlı şarj-deşarj edilebilmesi ve uzun ömre sahip olması istenir. Tüm bu nedenlerden dolayı, elektrikli araç akü paketleri, akü sistemlerindeki ısıyı gidermek ve akü paketi/modül/hücre boyunca eşit sıcaklık sağlamak için kapsamlı soğutma sistemleri içerir. Dolayısıyla günümüz elektrikli araç araştırma geliştirme çalışmaları bu konu üzerine odaklanmıştır. Bu tezde, elektrikli araçların batarya sistemleri süper elips geometriye göre 3D katı modelleme programı ile parametrik olarak tasarlanmış ve batarya sistemlerinin ısıl yönetimi gerçekleştirilmiştir. Isı yönetimi çalışmaları ANSYS CFX'te yapılmıştır. Belirlenen farklı parametrelerin batarya hücre sıcaklığı üzerindeki etkisi incelenmiştir. MATLAB ile, belirlenen farklı parametrelerle D-Optimal deney tasarımı oluşturulmuştur. Yine MATLAB'te kısıtlı fonksiyonlu lokal optimizasyon ve genetik algoritma optimizasyonu olarak iki alternatifli optimizasyonla minimize çalışması yapılmıştır. Elde edilen optimum değerler ve bulunan maksimum sıcaklık, CFX'te yeniden analiz edilmiş ve sağlaması yapılmıştır. Buna göre yapılan analizler ve optimizasyon sonucunda farklı parametrelerin ve geometrilerin ısıl performansa etkisi araştırılmıştır.

Anahtar Kelimeler: elektrikli araçlar, ısıl yönetim, süper elips, CFX, MATLAB, deney tasarımı, optimizasyon

To my dearest family and spouse…

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NOMENCLATURE

EV	: Electric Vehicle
ECU	: Electronic Control Unit
ICE	: Internal Combustion Engine
ICEV	: Internal Combustion Engine Vehicle
CV	: Conventional Vehicles
BT	: Battery Technology
CFD	: Computational Fluid Dynamics
TM	: Thermal Management
CO_2	: Carbon Dioxide
HV	: Hybride Vehicle
PEM	: Proton-Exchange Membrane
Pb-acid	: Lead-Acid
Ni-Cd	: Nickel Cadmium
NiMH	: Nickel Metal Hydride
Li-ion	: Lithium Ion
Li-Po	: Lithium Ion Polymer
$LiFePO_4$	: Lithium Iron Phosphate
LiS	: Lithium Sulfur
Zn-Air	: Zinc Air
Li-Air	: Lithium Air

1. INTRODUCTION

1.1. Overview of Electric Vehicles

Although energy is considered as a convertible currency for technology, it is an important part especially in human life and ecosystem. This has made energy a highly controversial subject today. With industrialization and globalization, energy demand has been increasing day by day. The fact that the world population grows by 2% each year also means that the need for energy increases. The developed lifestyle and energy demand are increasing together, and rich industrialized economies, which contain 25% of the world's population, consume 75% of the world's energy supply (Dunderdale, 1990). 80% of the energy requirement in the world is provided from fossil fuels. This share is quite high compared to nuclear and renewable energy sources. This makes fossil fuels such as oil, gas and coal the main source of energy globally. However, fossil fuels have huge disadvantages to the environment. It causes climate change especially due to emissions and this directly affects the environment and human health. According to the World Health Organization, 320,000 people are expected to die only originating from this climate change (Renewable Energy World, 2003). 25% of the emissions of fossil fuels that affect people and the environment so negatively belong to the transportation sector. In addition, oil reserves are concentrated in very few countries around the world, and this has become an important source of political conflict due to the high energy supply. These negative situations have made it very important that the transportation sector is compatible with a sustainable energy system (Kristoffersen, Capion and Meibom, 2011).

Internal combustion engine vehicles (ICEV), which have the biggest share in the transportation sector, are causing major problems in the atmosphere by using fossil fuels as the main source today. In this case, experts aim to develop alternative vehicles against ICEV. These vehicles are electric and hybrid vehicles (HV) that can be described as more environmentally friendly. Advances in battery technology (BT) have shown that electric and HVs can be used as much as conventional vehicles (CV), and have entered the competition lane.
While experts are still working on some of the problems of electric vehicles (EV), EVs offer important solutions and alternatives to the disadvantages of CVs, with sustainability, quiet operation, low operating costs and substantially low emissions.

1.1.1. Vehicle Types

1.1.2. Internal Combustion Engine Vehicles

Internal Combustion Engine (ICE) is a type of engine used in various vehicles today, powered by gasoline, LPG or diesel. These engines convert heat energy into mechanical energy. Although ICEVs have advantages such as long range and fuel availability, they have negative situations due to fuel consumption, cost and environmental effects.

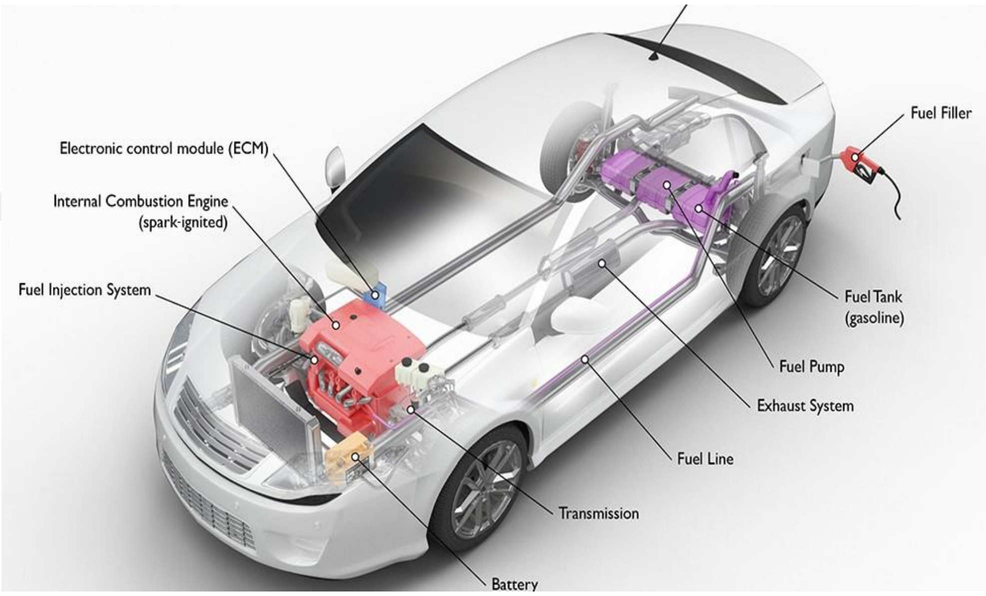


Figure 1.1. Overview of ICEV (Regans wedding cars, Retrieved from www.reganswеddingcars.com)

General advantages and disadvantages of ICEs are listed below (Çetin, 2016. Retrieved from www.muhendishane.org):

Advantages:

- Excessive volumes of fuel can be stored
- The energy density of the fuel increases the range that the vehicle can travel positively.
- The fuel to be stored is added to the fuel tank in a short time.
- Since fuel stations are quite common, they are more preferable in usage.

Disadvantages:

- Not all fuel energy can be used for movement. Most of the energy is lost in the powertrain.
- Since the fuel is fossil-based, it is not renewable.
- Fossil-based fuels have a significant impact on global warming and environmental pollution since they have high carbon dioxide emissions.
- Since a renewable resource cannot be used for energy, meeting fuel needs creates a negative impact in terms of cost.

Especially in recent years, significant improvements have been made ICEs and although demand has increased, fossil fuels that cause serious political and social conflicts and environmental pollution are needed.

1.1.3. Electric Vehicles

EVs are vehicles that are operated only with electrical energy sources such as batteries and use only electrical power in vehicle movement. There is almost no emission in these vehicles. Therefore, it is a type of vehicle that looks environmentally beneficial. However, even though the emission is zero while the vehicle is in motion, there is also emission during the production of the energy used by the vehicle. In this context, in order to make a healthy evaluation, the energy consumed by the vehicle must be followed and analyzed from the moment the energy is produced (Çetin, 2016).

The general overview of the EV is shown in Figure 1.2. :

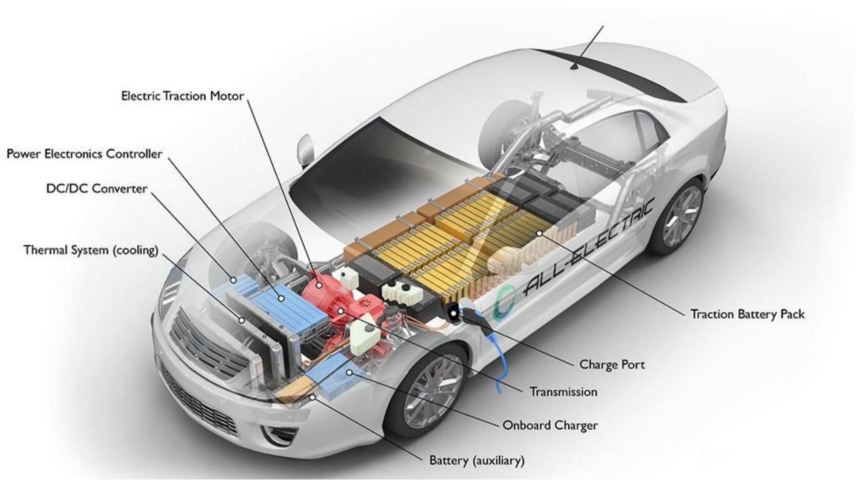


Figure 1.2. The general view of the EV (Alternative Fuels Data Center, Retrieved from www.afdc.energy.gov)

EVs are not as complex as ICEVs. Since it does not contain any mechanical gearbox, the vehicle is simpler, reliable and more energy efficient. While efficiency in ICEVs is 30%, efficiency in EVs can exceed 90%.

The general advantages and disadvantages of EVs are listed below (Sezen and İşler, 2017):

Advantages:

- Acceleration time is very short thanks to the high torque of the electric motor.
- It works quietly.
- While the vehicle consumes electricity during use, it can also generate electricity, such as braking, downhill acceleration, solar panel applications. It is especially ideal for electric buses and trucks.
- There are not many parts in EVs such as spark plugs, injectors, engines and connections, starter motor, oils, oil and fuel filters, gas tank, igniters and connections, powertrain, gasoline and exhaust pipes.
- Compared to conventional cars, there is almost no restriction in vehicle design. The life of the battery may be over, however, it is easy to switch to the new battery thanks to the technology that is constantly being renewed.
- There are no periodic maintenance expenses.
- It has zero carbon dioxide (CO_2) emission value.
- Many countries have low or no taxes such as SCT and MTV. In fact, in countries such as Norway, France, USA, there is an incentive in the purchase of EVs from 2,500 Euros to 7,500 Euros.
- The electric motor is cheaper, long-lasting and easy to replace. Less mechanical parts are required.
- It can be adapted to a conventional car, thus becoming hybrid.
- The existence of oil is finite; the electricity supply will remain as long as the solar system exists.
- This is because fuel costs are at least one-tenth cheaper than other vehicles.

Disadvantages:

- EVs are obliged to provide effective protection and insulation against water and moisture. However, this is no longer the case for many models produced today.
- EVs are not suitable for long-distance use due to the scarcity of charging stations.
- In today's technology, although the range problem is fixed, there is a range problem for EVs in general.
- Battery performance is affected by hot and cold climatic conditions. Today, the search for the most efficient and effective battery is still ongoing.
- They have long charging times. For example, charging time from level 2 to full filling can last up to 7 hours.
- Another disadvantage is that the batteries are still at high cost and in the last 7-10 years, the price / performance comparison is weak in terms of lifetime.

In addition to these disadvantages, the specific energy of gasoline is quite high compared to electrical energy. Providing the same energy levels for the two types of fuel means a large battery pack in EVs. This returns to the vehicle in weight and cost. Problems related to the battery have been the subject that experts are working on most today. Significant research is underway to increase the capacities, durability and efficiency of batteries, capacitors and fuel cells.

1.1.4. Hybrid Vehicles

HVs today represent an ICEV powered by electric motors. The purpose of HVs is to reduce gas consumption. To achieve this, they use the electric motor instead of the gasoline engine at low speeds, thus providing partially 0 emission emissions. The energy required for the operation of the electric motor is charged to the batteries when the gasoline engine is started or during braking. Therefore, there is no need to charge these vehicles by connecting them to electricity.

The general overview of the HV is shown in Figure 1.3.:

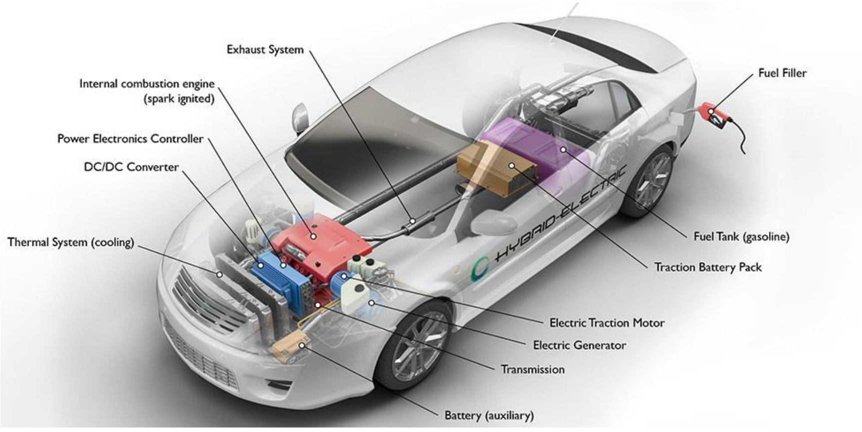


Figure 1.3. The general view of the HV (Alternative Fuels Data Center, Retrieved from www.afdc.energy.gov)

The general advantages and disadvantages of EVs are listed below (Keskin, 2009):

Advantages:

- Regenerative braking capability minimizes energy loss. It feeds the batteries by restoring the energy used when the vehicle stops or slows down.
- Since the ICEs are sized to meet the average load, not the peak load, the weight of the engine decreases.
- Fuel efficiency is greatly increased.
- Emissions are significantly reduced.
- Since HEVs can work with alternative fuels, they are not so dependent on fossil fuels.

Disadvantages:

- The vehicle largely depends on the ICE.
- The range problem is encountered while driving with the electric motor. Driving distance with electric motor is limited to 40-100 km.
- It is more costly compared to vehicles with ICEs.

1.1.5. Fuel Cell Vehicles

A series of electrically powered HVs of fuel cells using hydrogen can be called as fuel cell vehicles. The electricity produced by fuel cells can be used for both power the engine and store energy. In this way, it is predicted that the vehicle can produce its own energy and the range problem will disappear (Chan, Bouscayrol and Chen, 2010).

The general overview of the fuel cell vehicle is shown in Figure 1.4.:

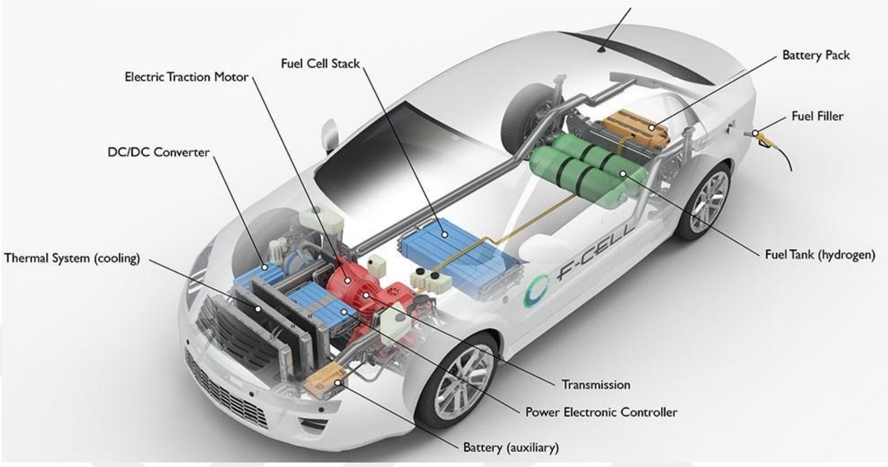


Figure 1.4. The general view of the fuel cell vehicle (Alternative Fuels Data Center, Retrieved from www.afdc.energy.gov)

The general advantages and disadvantages of fuel cell vehicles are listed below (Muthukumar et al., 2020):

Advantages:

- No harmful vehicle emissions
- Much better fuel efficiency
- Re-fuelling time is much lower than electric cars
- Hydrogen fuel can be generated in eco-friendly way
- Much fewer chemicals at pump
- Fit into current gasoline infrastructure
- Hydrogen fuel cells are durable
- Cost falling consistently
- Many safety measures in-place

Disadvantages:

- Price already lagging behinde electric cars
- Few places to re-fuel currently
- Currently more expensive fuel than gasoline
- Expensive to store and transport hydrogen
- Lots of greenhouse gas emissions (currently)
- Highly flammable
- Fossil fuels needed to produce hydrogen fuel cells
- Electric cars are more efficient

1.2. Technological Developments In Electric And Hybrid Vehicles

Although EVs appeared in the 20th century, they are dating back to the 18th century. The first EV model was developed by Professor Stratingh in the Netherlands in 1835 (Ünlü et al., 2003). The range length was of great importance in EVs. However, as the physical situation in the transportation network is not suitable for long range, developments related to EVs started to decrease after a while. In addition, the reproduction of oil stations, technological developments related to ICEVs and the fact that these vehicles were more common, cheaper and accessible in the market also supported the decrease in developments related to EVs.

In the Middle East, where oil density was at the highest level, the Arab oil embargo caused an increase in oil prices in the 1970s. At the same time, researches on electric and hybrid vehicles have been revived with the adoption of environmentally friendly approaches, especially in Europe and America. Although prototypes were produced at that time, they were not in demand in the vehicle market due to battery problems and high prices (Dinçer, Hamut and Javani, 2017). In the late 20th century, the sale of over 4000 EVs changed the balances again. Environmental concerns and the ever-increasing price of oil have brought EVs back into the range of passenger cars and commercial vehicles (Santiago et al., 2012).

According to the World Energy Council Turkish National Committee surveys, EV sales worldwide in 2018 are shown in the Figure 1.5.:

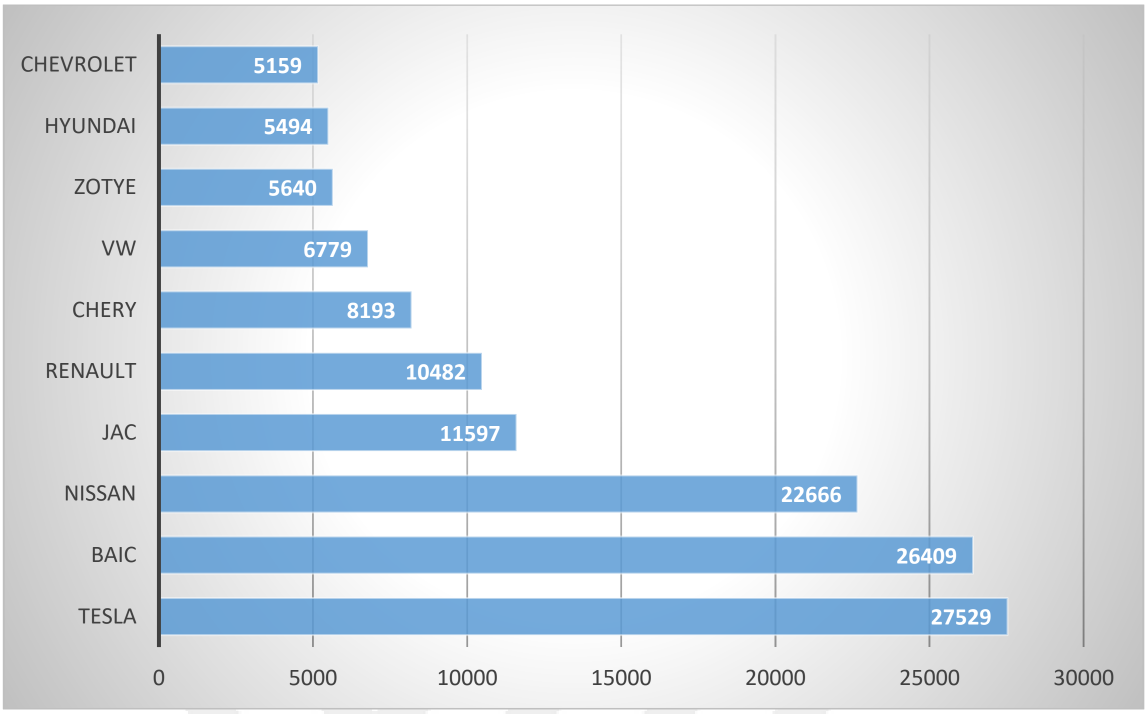


Figure 1.5. EV Sales Worldwide in 2018 (Statista, 2018. Retrieved from www.statista.com)

The comparison of EV sales in the international market by evaluating the first quarters of 2017-2018 is also shown in figure 1.6.:

Figure 1.6. The comparison of EV sales in first quarters of 2017-2018 (Ev-volumes, 2018. Retrieved from www.ev-volumes.com)

As seen from the 16th and 17th references, it is observed that the interest in EV has increased with the increase in vehicle sales worldwide. Again, looking at the tables, it can be said that the company selling the most EVs is Tesla and the country with the largest growth rate in the sales of EVs is China.

1.2.1. Developments In Electric And Hybrid Vehicles In Turkey

Automotive companies in the world, in general, are conducting active work in Turkey's market. These companies are carried out on both design, production, and research and development. Apart from traditional productions, Turkish companies also show importance to the rising trend, which is EVs. Turkish government also offers incentives for the production of EVs and lifts all legal barriers. (Yılmaz and Ustaoğlu, 2013)

Turkey is among the developing countries since the 2000s however, a budget deficit of 54 billion dollars affects the country excessively. This deficit is mostly due to energy imports. Transportation in energy use has the highest share with 62% and this rate means a budget deficit of $ 33.6 billion. It is predicted that the increase in e-mobility will decrease energy imports. EVs can be charged at night when electricity is lower priced tariff in Turkey.

There are three main factors that the Turkish state is motivated about EV technology;

I. Turkey has a big automotive industry and electric transport can provide many benefits to the country.
II. The carbon emission caused by ICEs poses a great threat for climate change.
III. EVs can reduce oil imports, which positively affects the budget deficit. (Yıldız, Ustaoğlu and Incekara, 2014)

The history of EVs in Turkey can be summarized as follows (Dinçer et al., 2017):

- Turkish bus manufacturer Temsa developed Avenue Hybrid, which consumes 25% less fuel and has lower CO_2 emissions than ICE buses in 2009.
- In 2009, Otokar announced that the hybrid city bus Doruk 160LE was consuming 20% less fuel.

- TOFAŞ, Turkey will take place in the serial production of the electric version of the Doblo EV to start work at the end of 2009. In 2010, the prototype of the vehicle was introduced.
- In 2010, the production of Fluence Z.E. was started in Oyak Renault company in Bursa. However, production was stopped in 2013 due to low sales of the vehicle model.
- Derindere Motor Vehicles (DMV), which means the beginning of 2013 the first EV with Turkish approval certificate for an EV in Turkey took DME All Electric to market and made its first test drive. The company plans to produce 100 of this vehicle every month. The motor and batteries for vehicles are imported at the moment, however, the electronic control unit (ECU) has been developed in Turkey.
- Malkoçlar Automotive, in the middle of 2013, with R & D and manufacturing all made in Turkey (except electric motor) has developed EV that can travel 100 km. The vehicle is designed in 2 types, one with 2 seats and the other with 4 seats. In the design, it is aimed mainly for city travels and commercial usage.
- Founded in 2014, designed by GEN Automotive TM-480 is a prototype vehicle production in Turkey continues. The vehicle was exhibited at the R&D and Innovation Summit held in Istanbul on October 17-18, 2018. However, due to the certification and procedure procedures, it is estimated that the vehicle will start 2-3 years of mass production.
- Under the leadership of the Ministry of Science, Industry and Technology, the establishment of a Turkish automobile brand in line with 2023 national technology targets and the industrialization of its first products came to the agenda. To this end, TÜBİTAK MAM started the necessary studies at the beginning of 2015. The first vehicle before 2020 began to introduce all the necessary infrastructure and preparation for the Turkey market. The vehicle was introduced in December 2019. The brand will be launched in 2020 and the factory will be opened in 2021. The first vehicle will be produced in 2022 and will be available for sale.

1.3. Energy Storage Systems

The use of the appropriate energy storage system for the application in question is becoming one of the main selection criteria for electric and hybrid electric vehicles. In this study, batteries, super capacitors, flywheels and fuel cells will be explained.

1.3.1. Batteries

Batteries are the most common devices used to store electrical energy. The performance of EVs is highly dependent on the battery. As the performance of the batteries is mainly dependent on battery chemistry, research has focused on battery chemistry. In every chemical reaction device, battery chemistry deteriorates over time, which directly affects the overall performance of the vehicle. For this reason, battery management systems have been developed in order to delay the breakdown time and ensure that it progresses gradually. The battery management system provides the control by conditioning the battery in different conditions and loads and keeps the thermal management (TM) in the battery cells in balance. Accordingly, it is aimed to decrease the cost as well as increasing the lifetime, safety and performance of the batteries.

Significant improvements have been made in terms of mixing chemistry in the past. In addition, the current Li-Ion chemistry has a wide share in the industry range. Battery types and features are shown in the table below:

Table 1.1. Comparison of EV Battery Types (Yong, Ramachandaramurthy, Tan and Mithulananthan, 2015)

Battery type	Nominal voltage (V)	Energy density (Wh/kg)	Volumetric energy density (Wh/L)	Specific power (W/kg)	Life cycle	Self discharge (% per month)	Memory effect	Operating temperature (°C)	Production cost (S/kWh)
Lead acid (Pb-acid)	2.0	35	100	180	1000	< 5	No	-15 to +50	60
Nickel-cadmium (Ni-Cd)	1.2	50-80	300	200	2000	10	Yes	-20 to +50	250-300
Nickel-metal hydride (Ni-MH)	1.2	70–95	180-220	200–300	< 3000	20	Rarely	-20 to +60	200-250
ZEBRA	2.6	90–120	160	155	> 1200	< 5	No	+245 to +350	230-345
Lithium-ion (Li-ion)	3.6	118–250	200-400	200–430	2000	< 5	No	-20 to +60	150
Lithium-ion polymer (LiPo)	3.7	130–225	200-250	260–450	> 1200	< 5	No	-20 to +60	150
Lithium-iron phosphate ($LiFePO_4$)	3.2	120	220	2000–4500	> 2000	< 5	No	-45 to +70	350
Zinc-air (Zn-air)	1.65	460	1400	80–140	200	< 5	No	-10 to +55	90–120
Lithium-sulfur (Li-S)	2.5	350–650	350	–	300	8–15	No	-60 to +60	100–150
Lithium-air (Li-air)	2.9	1300-2000	1520-2000	–	100	< 5	No	-10 to +70	–

Also, The batteries have 4 different shapes, small and large cylindrical, prismatic and rectangular (Pesaran, Kim and Keyser, 2009).

Cylindrical cells have high volume. However, it requires battery enclosure to prevent it from expanding during charging. It is also structurally more resistant to shock and vibration than other battery geometries.

Since prismatic cells are mounted to the vehicle with bolts, they are easy to replace. It has better volume efficiency compared to cylindrical cells. In addition, this battery geometry is covered with a semi-hard plastic casing.

Rectangular batteries need protective covers just like prismatic cells. This leads to extra volume and weight gain in the vehicle. Rectangular packs have soldered tips and have high energy density without extra packaging.

The automotive industry focuses on battery-related work so that EVs can compete with CVs. Choosing the right battery is of great importance in EVs. Batteries are evaluated according to the criteria of providing long-lasting, low cost, compact, sufficient power in order to choose the right battery. Also, the memory effect is one of the most important concepts for batteries. The memory effect can be explained as follows: when the battery is not fully discharged, it can be defined as the situation where the device behaves abnormally due to low voltage when there is a gap behind the place where the charge begins. BT is applied in different fields such as energy, transportation, space and aviation, technology.

1.3.2. Super Capasitors

Electrochemical storage devices with high specific power values are called super capacitors. Electric energy can also be stored in super capacitors. Super capacitors are basically composed of two conductive plates and insulators. Insulators are also called dielectrics. Compared to conventional lead-acid batteries, super capacitors have 5 times higher specific power. In addition, these devices can be included in battery-based systems to separate power features. Thus, the life of the entire storage system can be extended (González, Goikolea, Barrena and Mysyk, 2016).

The use of super capacitors is very common in the use of photovoltaic panels. At the same time, the use of super capacitors has a large share in applications where portable electronic devices are used. The advantage of using super capacitors in these devices provides fast charging feature and short charging time. Super capacitors can operate in the temperature range of 40 to 85 ° C. This feature is one of the advantages as it provides a wider temperature range compared to conventional batteries (Winter and Brodd, 2004).

1.3.3. Fuel Cells

Systems that produce electrical energy by a suitable fuel (usually hydrogen) and the electrochemical reaction of the oxidizer are called fuel cells. As a result of the electrochemical reaction of fuel and air, chemical energy turns directly into electrical energy. The fuel cell reaction can also be considered as a reverse reaction to electrolysis. Due to the reaction, pure water and heat are released.

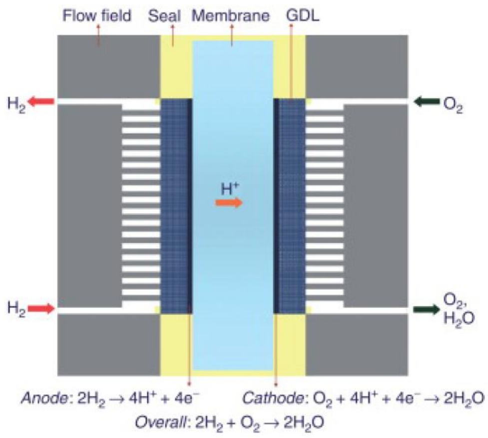


Figure 1.7. Cross-sectional view of a proton-exchange membrane (PEM) unit cell. (The fuel (H2) is oxidized at the anode catalyst layer (ACL) and the oxidant (O2) is reduced at the cathode. GDL, gas diffusion layer) (Zhang et al., 2013)

As seen in the figure, the fuel cell consists of electrolyte and permeable porous anode and cathode electrodes. The electrolyte is located between these electrodes. Fuel is sent to the negative anode pole and air or oxygen to the positive cathode pole. As a result of the reaction of this fuel and air, a potential difference occurs between the anode and cathode. This difference creates electrical voltage. As a result of recreation, heat and water are released. If the fuel used contains carbon, carbon dioxide also occurs as a result of the reaction (Zhang et al., 2013).

1.3.4. Flywheels

Flywheels are one of the oldest known kinetic energy storage devices. Flywheels store excess energy generated in the system. When the load demand increases, it transfers the energy it stores to the load and provides balance. Flywheels can be considered as the ideal solution in mechanical systems. For this reason, it can be said that they act as mechanical batteries for flywheels. Flywheels are used in today's technology due to their durable materials. While its task in the past was to store mechanical energy and then converted it to kinetic energy when needed, it also provides the conversion of electricity and mechanical energy with the technology that is developing today.

Flywheels take the energy as electrical energy at the entrance and convert it into kinetic energy from the start of the engine. It stores excess energy and extracts it in the form of electrical energy like generator.

The following image shows the components in the flywheel energy storage system:

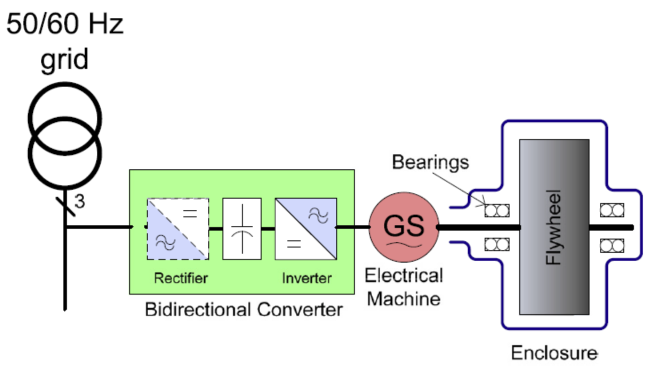


Figure 1.8. Components of flywheel energy storage system (Sebastian and Alzola, 2012)

1.4. Battery Technologies In Electric Vehicles

Batteries are the most commonly used electrical energy storage device in EVs today. It is first-order effective in almost all subjects such as the features and use of batteries, vehicle performance, cost, and safety. Today, studies on the chemistry of batteries are continuing since battery chemistry is directly related to the performance of the battery. Studies focus on this, as battery performance also means greater range, reliability and safety. As with almost all chemical processes, battery chemistry deteriorates over time and affects battery performance. Accordingly, the performance of the vehicle is equally affected. For this reason, there is a need for a battery management system that continuously receives data from the battery, makes the situation forecast and balances the charge / discharge state, and also provides TM of the battery cells.

The main purpose in the automotive industry is to reduce the fuel consumption, reduce emissions and reduce the cost of production, as well as the ergonomic design, reliability and safety. As mentioned earlier in our study, in order for EVs to compete with CVs, these features must be provided and their disadvantages must be overcome. In this regard, the batteries act as a heart for EVs. With the right battery selection and proper use of the battery, EVs will be able to compete with CVs. No BT provides point shot for any vehicle. However, more efficient results are obtained by optimizing the use of the battery.

In the most basic sense, battery types will be mentioned in order to comprehend the battery chemistry.

1.4.1. Lead-Acid Battery (Pb-acid Battery)

Lead acid batteries were commercialized in the early years when they were first introduced in 1859. It has widespread use in motor vehicles. Together with other batteries, it offers advantages such as low price, high cell voltage, high electrochemical activity, high reliability (Sharma, Panwar and Tripathi2 2020).

However, although this battery chemistry is cheap, it has a low energy content. Cycle life is still a limiting factor for the use of these batteries in EVs. Therefore, their use has still not gone beyond industry and vehicle applications. Examples of applications are automobile starting, lighting and ignition.

The image below shows the energy storage in a Pb-acid battery cell and the reactions occurring at that time:

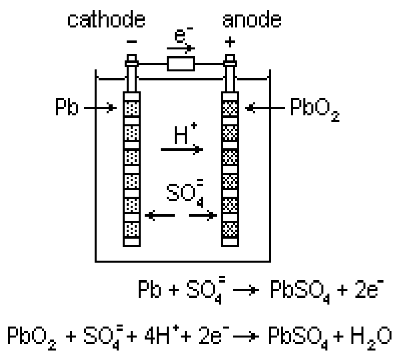


Figure 1.9. Pb-Acid Storage Cell (Lead, 2004. Retrieved from www.mysite.du.edu)

1.4.2. Nickel Cadmium Battery (Ni-Cd Battery)

Nickel batteries were first introduced by Edison in the early 1900s. Edison used this battery as a power source in various applications. Ni-Cd batteries have two important structures, ventilated and sealed. The main advantages of Ni-Cd are its high temperature capacity compared to other battery types and its excellent lifetime up to ten years in the optimum temperature range (30 ◦C-80 ◦C). However, on the other hand, these batteries quickly lose their capacity to self-discharge at ambient temperature (Pistoia, 2008).

Since Ni-Cd batteries have more pronounced environmental effects, these batteries have been replaced by nickel metal hydride (NiMH) and lithium ion (li-ion) batteries.

1.4.3. Nickel Metal Hydride Battery (NiMH Battery)

NiMH batteries replaced Ni-Cd batteries in the 1960s due to their advantages such as lower pressure, higher energy and lower costs than Ni-Cd. Also, the Ni-MH battery was a good battery candidate for EVs for those with a non-toxic recyclable material. In the early 1990s, the Ni-MH battery began to be widely used in electronic devices and was commercialized as a rechargeable battery (Huggins, 2010).

Ni-MH batteries have limited high rate capacity, weak low temperature capacity and also high self-discharge, such as important problems to be solved. Oxygen reactions in these batteries generate considerable heat and the temperature rises during charging. It can produce dangerous gases as a result of chemical reactions. Electrodes may deteriorate quickly due to water loss. These features explain serious disadvantages for Ni-MH batteries.

1.4.4. Lithium-Ion Battery (Li-Ion Battery)

Battery features have a very important area in electric and hybrid vehicle technology. For this reason, batteries are expected to have important features. The battery chemistry we have examined so far has low energy and power density compared to li-ion batteries. Li-ion batteries are the most used batteries for batteries today. Lithium is the lightest metal. It also has cells that provide energy density with high voltage. In addition, having a small ion diameter is a useful feature for diffusion. Such features make li-ion batteries an important candidate in electric and hybrid vehicle applications.

The first lithium batteries began to be developed in the 1970s. Rechargeable lithium metal batteries were attempted to be commercialized in the 1990s, but problems such as safety and long charging times were encountered. After the advantages of using lithium metal in energy applications were noticed in 1970, Exxon produced the lithium battery for the first time in 1972 by producing a cathode in the TiS_2 structure (lithium metal was used as an anode). In 1980, it was discovered that layered sulfur containing cathode materials did not remain stable during long cycles. Goodenough et al. suggested that metal oxides should be used as cathodes as alternative materials (Polat and Keleş, 2012). Sony first developed this view in 1991, producing the first commercial Li-ion battery. In these cells, where $LiCoO_2$ is used as cathode and carbon as an anode, a potential of 3.6 V was obtained and the production of li-ion batteries that were stable during long cycles was achieved.

Commonly used Li-Ion battery types are shown in the table below.

Table 1.2. Features of Some Lithium Battery Cells (Whittingham, 2012)

Chemistry	Size	Wh/L theoretical	Wh/L actual	%	Wh/kg theoretical	Wh/kg actual	%
$LiFePO_4$	54208	1980	292	14.8	587	156	26.6
$LiFePO_4$	16650	1980	223	11.3	587	113	19.3
$LiMn_2O_4$	26700	2060	296	14.4	500	109	21.8
$LiCoO_2$	18650	2950	570	19.3	1000	250	25.0
Si-$LiMO_2$ Panasonic	18650	2950	919	31.2	1000	252	25.2

As with all other batteries, li-ion batteries have disadvantages. Especially, these batteries have limited lifetimes at high temperatures and they have some safety-related problems in their large, multi-cell models. In challenging working conditions, such as rising to high temperatures and high limits during charging, oxygen release may occur in the cathode and thermal runaway and explosions may occur as a result of the reaction of oxygen with a flammable electrolyte. Therefore, although $LiFePo_4$ chemistry has relatively low nominal voltage, it is widely used since it has stronger covalent bonds than the chemicals mentioned above. Furthermore, this makes this chemistry relatively safe.

When all these features are evaluated, higher energy concentrations are needed than the ones available in li-ion batteries, which are preferable candidates, so that EVs can compete with CVs. Therefore, in order to meet all these needs, radical approaches and serious studies on battery chemistry are required.

Temperature management in the battery with different parameters was examined. Li-ion batteries are more preferable compared to other battery types thanks to their light material, high energy density, high power density, low discharge rates and long life. In this thesis, li-ion batteries were preferred as the battery type.

Overheating and unbalanced temperature distribution cause rapid deterioration of cells, shortening of battery cycle life, and negative effects on capacity and battery safety. Overheating and unbalanced temperature distribution cause rapid deterioration of cells, shortening of battery cycle life, and negative effects on capacity and battery safety. can be. Motloch et al. (2002) showed in their studies that a 1 ° C increase in the temperature of the battery in the 30-40 ° C battery temperature range reduced the battery life time by 2 months (Motloch et al., 2002) In addition, battery performance is negatively affected by low ambient temperature. Therefore, effective thermal performance management is required to ensure optimum performance of batteries.

Heat management in li-ion batteries selected in this study consists of 4 main basic functions:

1. Cooling: When the temperature of the battery increases, it is the cooling of the batteries to reach the ideal operating temperature.
2. Heating: It is the heating of the batteries to the ideal operating temperature when the temperature decreases in the battery.
3. Insulation: It is to provide insulation to prevent the battery from being affected by extreme outdoor temperatures.
4. Ventilation: Ventilation is required to discharge dangerous gases in the battery group. In some systems this function is combined with cooling and heating functions.

1.5. Working Conditions Of Lithium-Ion Batteries

The performance of li-ion cells is dependent on temperature and operating voltage (voltage) values. Li-ion cells operate safely at the limit (minimum and maximum) values of voltage and temperature. Otherwise, permanent damage to the cells will occur. In overvoltage situations, when the charge voltage exceeds the maximum cell voltage it causes excessive electric current. This may cause a short circuit between the electrodes, causing deterioration of the electrode materials. As with overvoltage, undervoltage can cause electrode materials to deteriorate. These problems can result in battery short circuit and / or capacity losses.

The graph showing the effect between temperature and performance is given below:

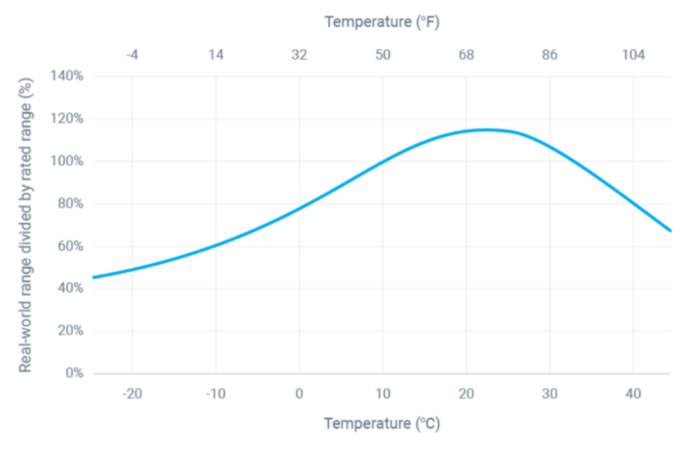


Figure 1.10. Battery-temperature performance curve (Electric Autonomy, Retrieved from www.electricautonomy.ca)

When looking at the chart, it is seen that the ideal battery temperature for maximum battery performance is between 15-40 ° C. The narrow range is an indicator of how important performance is.

Figure 1.11. shows the cycle amount depending on the operating temperature range of the battery cells.

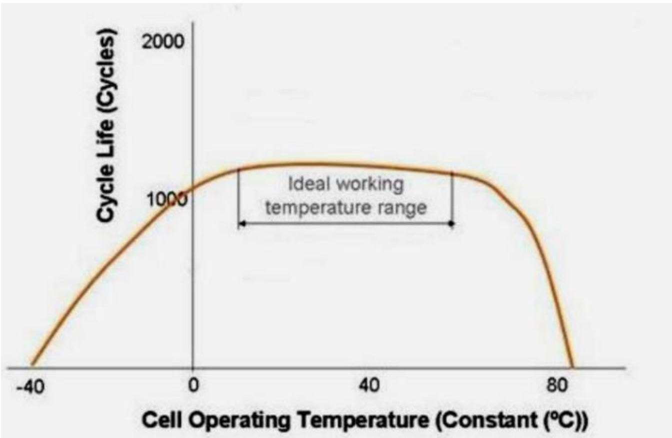


Figure 1.11. The operating temperature-cycle curve of the battery cell (Battery Thermal Management System, Retrieved from www.researchgate.net)

The cycle amount is one of the most important factors determining the life of batteries. The entire process of a charge and subsequent discharge is called a cycle. The change in cell operating temperature affects the amount of cycle. The situation indicated in this graph is that the ideal operating temperature range is approximately 10-60 ° C. Temperatures lower than 10 ° C and higher than 60 ° C negatively affect both the operating performance and the cycle life, as they negatively affect the battery materials.

In general, when we evaluate both the operating performance and cycle life parameters together, the ideal operating temperature range of the battery is expected to be in a wider range 10-60 ° C. This value range should be considered especially for battery cooling.

1.6. Thermal Management Technologies For Batteries

1.6.1. Air Cooled And Heated System

Air is used for cooling and heating functions in this heat management technology. The air entering the system may be the air coming from the atmosphere or the cabin. This system is called passive cooling / heating system. Or the air entering the system can be conditioned air after the heater or evaporator of an air conditioner. This system is called active cooling / heating system. A passive system can have a cooling / heating power of up to one hundred watts, while an active system can have a cooling / heating power of up to 1 kW.

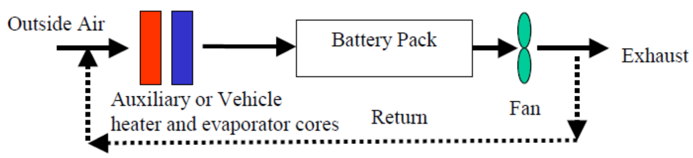


Figure 1.12. Active air-cooled and heated system (Wang, Jiang, Li and Yan, 2016)

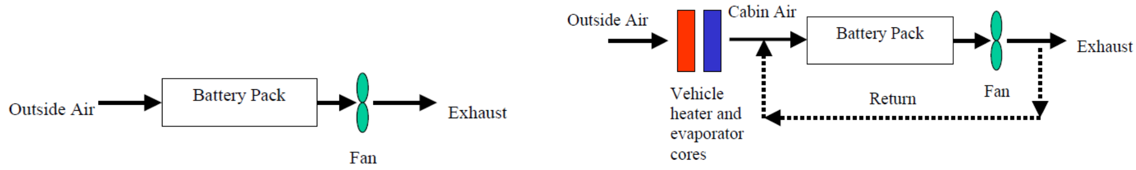


Figure 1.13. Passive air-cooled and heated system (Wang et al., 2016)

1.6.2. Liquid-Cooled And Heated System

Liquids are other types of heat transfer methods used in heat transfer. Generally, there are two groups of fluids applied for TM systems. Liquids such as mineral oil (direct contact liquid) that can directly contact the battery cells and liquids such as ethylene glycol and water mixture (indirect contact fluid) that may indirectly contact the battery cells. Depending on these fluid groupings, different systems have been designed. Battery packs for direct contact liquid are immersed in mineral oil. A possible system for indirect contact liquid could be a protective cover around the battery pack, with separate piping around each pack, by placing the battery packs on the cooling / heating plate, or by combining the battery pack with the cooling / heating fins and plates.

Liquid systems can be grouped as passive and active as in air systems. In passive liquid cooling systems, the radiator is generally used as a cooling plate. The pump circulates the heat transfer fluid in a closed system. The fluid circulation in the system absorbs the heat in the battery pack and expels the liquid through the radiator. The temperature between the ambient air and the coil significantly affects the cooling power. Therefore, placing a fan behind the radiator improves the cooling performance. However, if the ambient air is higher than the temperature of the coil and the difference between them is very small, the passive liquid system cannot be effective enough for cooling.

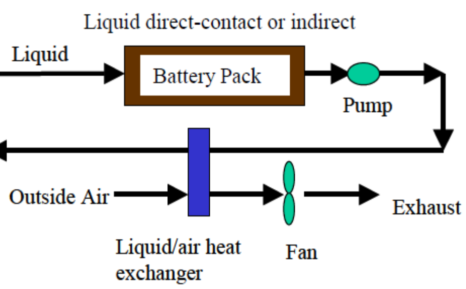


Figure 1.14. Passive liquid-cooled and heated system (Wang et al., 2016)

It is seen that there are two cycles in active liquid cooling systems. The first loop is one in which the heat transfer fluid is circulated by the pump and is similar to a passive liquid-cooled system. The second cycle is an air conditioning cycle. The heat exchanger works like an evaporator for cooling and connects the two loops. For the heating process, it acts as a condenser, which makes the heating cycle like a heat pump cycle.

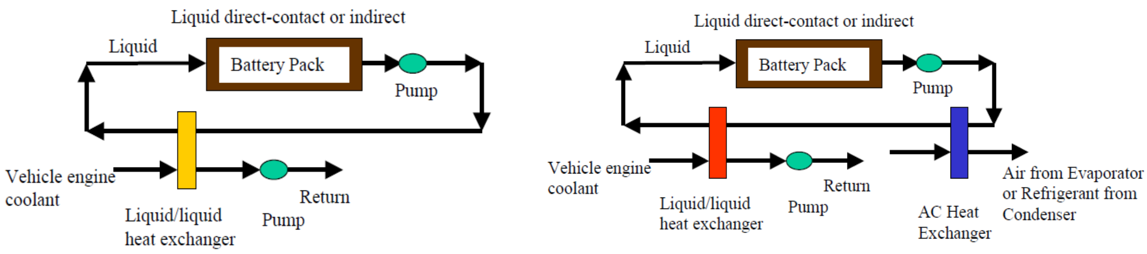


Figure 1.15. Active liquid-cooled and heated system (Wang et al., 2016)

1.6.3. Direct Refrigerant Cooling And Heating

Direct cooler heating and cooling systems are similar to active liquid systems in that they consist of air conditioning cycle. However, the refrigerant circulates directly in the battery pack as refrigerant.

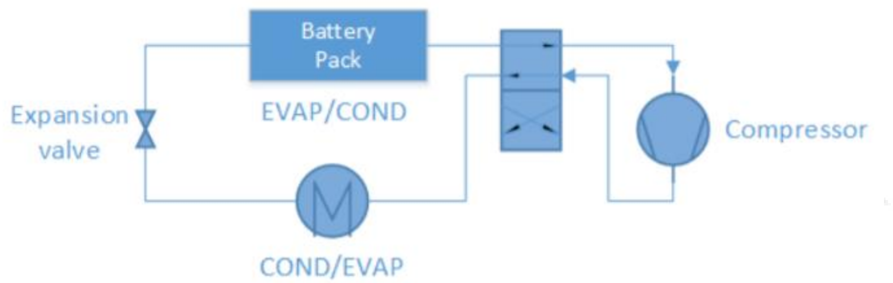


Figure 1.16. Direct Refrigerant Cooling and Heating System (Li and Zhu, 2014)

1.6.4. Phase Change Material (PCM)-Cooling And Heating

Materials with high heat of fusion that store and release the amount of heat at a fixed point during melting and solidification are called phase change materials. Phase change materials are solid. With the increase in temperature, heat is absorbed in the material as sensible heat. When the temperature reaches its melting point, heat is absorbed and stored as latent heat. This situation continues to the maximum point of latent heat without temperature increase in the material. Meanwhile, the material passes from solid form to liquid form. Later, when the material passes into liquid form, heat is absorbed as sensible heat.

The energy storage property of this material depending on the temperature is given in the figure below:

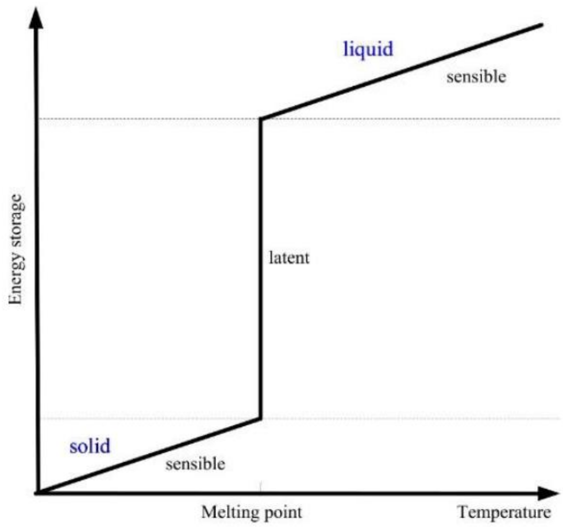


Figure 1.17. The relationship of temperature and energy storage of PCM (Li and Zhu, 2014)

Also, phase change materials can be combined with an air-cooled system or a liquid-cooled system to manage coil temperature.

1.6.5. Cooling And Heating With Thermoelectric Module (Peltier)

Thermoelectric coolers keep the temperature of an object in equilibrium, regardless of the surrounding temperature, while reducing the temperature of an object to below ambient temperature. Thermoelectric coolers can sometimes be called thermoelectric module or Peltier cooler. Thermoelectric coolers are semiconductors that work like a small heat pump. Thanks to a small voltage supplied from a direct current source, heat moves from one end of the module to the other. Thus, while one side of the module warms up, the other starts to cool simultaneously. This phenomenon can be reversed by the reversal of the positive and negative poles of the direct current source. A thermoelectric module can be used as a heater or cooler depending on its intended use.

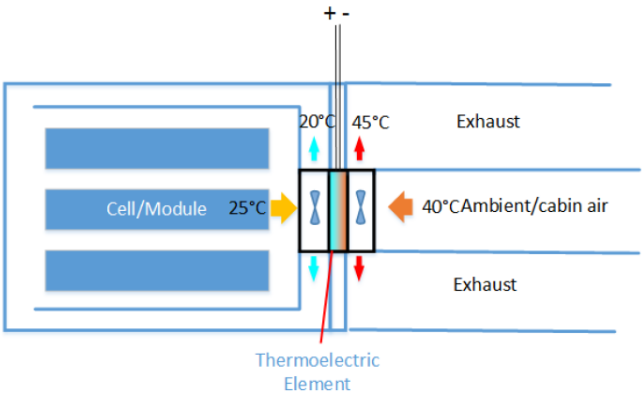


Figure 1.18. Thermoelectric cooling/heating system (Li and Zhu, 2014)

It's easy to switch between cooling and heating operation. To achieve that, the poles of electrodes need to be reversed.

1.6.6. Heat Pipe

Besides thermoelectric modules, heat pipe is another way passive air systems increase their performance. The heat pipe transfers heat from one area to another using the evaporation and condensation phase change. The inside of an empty metal pipe is filled with a chemical liquid that will carry the heat, and it carries the heat from one region to another in an endless cycle by taking advantage of evaporation and condensation. It consists of a vacuum sealed conductor. A typical heat pipe consists of 3 basic parts, the evaporator part (heat input / source), the part where the heat is carried, and the condensing part (heat output / output). In this system, the heat pipe uses water as the working fluid.

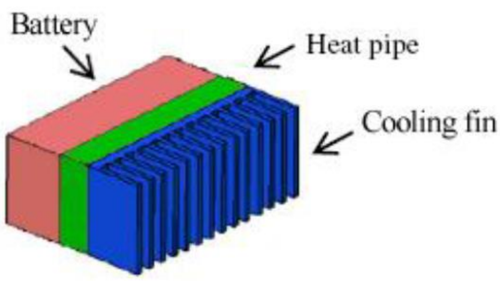


Figure 1.19. Scheme of heat pipe cooling system (Li and Zhu, 2014)

Compared to thermoelectric, a heat pipe is more reliable since it has no moving parts and no energy consumption. However, the heat pipe does not have a function to heat the battery.

2. LITERATURE REVIEW

In the world where energy conservation and environmental protection are a concern, the development of EV technology has accelerated since the 1800s (Chan, 1993). The first battery-powered EV was invented in 1834 about 50 years before ICEVs (Chan, 2007; 2013). EVs, which were quite popular until 1918, were preferred over gasoline-powered vehicles, and made many sales (Kwo Young et al., 2013). The continued development of gasoline vehicles, the increase in oil production, and the mass production of gasoline vehicles by Henry Ford in 1910 put an end to the use of EVs for transportation. By 1933, the number of EVs was reduced to almost zero.

Among the reasons why EVs remain behind their gasoline counterparts are slower and more expensive, their range is less, and the batteries used at that time have low energy density, long charging time and less durability (Chan, 1993; Nor, 1993; Xiao et al., 2015; Hirve and Vidyapeeth, 2018;). In addition, users were more concerned with cost-effective transport, as pollution-related environmental problems are still unpredictable. The fact that the fuel distribution infrastructure of ICEVs is more than the EV distribution infrastructure is shown as another reason why EVs remain in the background (Lynch and Salameh, 1997).

With the emergence of the oil crisis in the early 1970s, the increase in oil prices and the realization that fossil fuels are a limited resource have started to increase the interest in EVs again (Lukic et al., 2008; Chan, 2013; Muratoğlu and Akkaya, 2015; Xiao et al., 2015). The negative effects of the energy crisis, the rapid depletion of fossil fuels, the harmful gases emitted by ICEs and the efforts to reduce environmental pollution caused countries to change their energy policies (Chan, 2007; Tinğ et al., 2015). Many countries have started to implement regulations and special tax policies for the re-development of EVs (Sun et al., 2019). Accordingly, it is aimed to restrict domestic sales of CVs in France and England until 2040 (Li et al., 2019). In addition, tax cuts and credit support were applied for EV incentives in the USA, China, UK and Japan (Palmer et al., 2018; Li et al., 2019; Sun et al., 2019). EV sales are expected to reach 130 million levels in 2030 due to the countries' EV incentives and environmentally friendly approaches (Burd et al., 2021).

EV technology has developed in three different ways as battery EVs, hybrid EVs and fuel cell EVs (Kisacikoglu et al., 2011; Tinğ et al., 2015; Sun et al., 2019). EVs operate differently from ICEVs. The operation of battery-powered EVs is entirely powered by a battery, and is powered by a large rechargeable battery, an electric motor, a controller that sends electricity to the engine from the driver's accelerator pedal, and a charging system (Lynch and Salameh, 1997; Muratoğlu and Akkaya, 2015; Mersky et al., 2016; Hirve and Vidyapeeth, 2018). These parts of EVs replace the ICE, fuel tank, fuel line and exhaust system found in a conventional car. While the ICE is at the center of the operation of a CV, in rechargeable EVs, the system at the center and enabling the vehicle to operate is the batteries.

Hybrid EVs have two power sources. In these vehicles, an ICE and an electric drive system work together. Although HVs make up the largest proportion of the EV market, they are not completely independent of fuel (Matthews et al., 2017; Sun et al., 2019). The operating logic of EVs with fuel cells is slightly different from other EVs, and they benefit from the reaction of hydrogen and oxygen (Leitman and Brant, 2009). A fuel cell car is a type of electric car that uses a fuel cell or a battery alongside a fuel cell to drive the electric motor (Das et al., 2017; Sun et al., 2019). The common point of these three different vehicle technologies is the batteries used in the vehicle system and provide the chemical storage of electrical energy (Tinğ et al., 2015).

As in the past, the greatest technological challenge in selecting future EV concepts lies in the development of powerful yet low-cost battery systems (Frieske et al., 2014). Since low-cost battery cell production is crucial to the market success of EVs, battery cell manufacturers invest billions of dollars in new battery cell facilities, based on projected EV growth rates (Duffner et al., 2021).

The batteries used in EVs are required to have high power density and high energy density, as well as fast charge-discharge and long life (Chu and Majumdar, 2012). The battery system is a crucial factor in EVs, and the range of EVs is directly related to the battery capacities. Therefore, the need for higher energy capacity batteries is increasing (Budde-Meiwes et al., 2013; Tinğ et al., 2015; Halimah et al., 2019). However, today, no energy storage system has been able to meet all the requirements of hybrid and battery EVs (Khaligh and Li, 2010). Therefore, the biggest challenge in the EV industry is to develop the state-of-the-art battery system that best complements the technology (Tie and Tan, 2013). There are many battery systems from the past to the present, and studies are continuing to develop batteries with the most suitable parameters. R&D programs supported in many countries aim to develop advanced management systems, high efficiency motors and high energy density innovative batteries in both rechargeable and fuel cell types (Guarnieri, 2011).

A battery is a storage device consists of one or more electrochemical cells that convert stored chemical energy into electrical energy (Winter and Brodd, 2004; Tie and Tan, 2013). They generate electricity by releasing potential energy stored in the battery's chemicals (Tarascon and Armand, 2001).

Key considerations in the design of BT depend on the power density (Wkg^{-1}) and weight energy density ($Whkg^{-1}$) due to the design concept. However, BT must also be able to perform well in terms of energy efficiency, cycle life, cost, weight and charging characteristics (Kisacikoglu et al., 2011; N. Omar et al., 2011; Hirve and Vidyapeeth, 2018). The batteries used in EVs are quite different from those used in consumer electronic devices such as laptops and cell phones (Young et al., 2013). They need to handle high power (up to 100 kW) and high energy capacity (up to tens of kWh) at an affordable price in a limited space and weight (Young et al., 2013; Vidyanandan, 2019).

The current EV battery has relatively low energy density, which directly affects the maximum electric driving range of EVs (Tie and Tan, 2013). However, BTs in EVs have shown great advances in recent years. Today, there are various BTs with different rated voltage and energy density, and battery development studies are continuing by using different chemistries in order to produce batteries with the most suitable parameters (Muratoğlu and Akkaya, 2015).
The first BT used in transportation in the past is the lead-acid battery. The name of lead acid comes from the combination of lead electrodes and acid used to generate electricity. Lead-acid battery is a mature technology and, if an assessment is made in terms of cost for EVs, it is the most suitable battery type for energy storage (Enache et al., 2014; Miao et al., 2019; Asghar et al., 2021). However, low energy density and high weight pose a disadvantage (Armand and Tarascon, 2008; Yong et al., 2015).

The lead-acid battery was soon replaced with a nickel-based battery such as nickel-cadmium (Ni-Cd) and nickel-metal hydride (NiMH). Nickel-based battery is considered relatively mature technology and has higher energy density compared to lead-acid battery (Tubb, 1939; Armand and Tarascon, 2008).

Nickel-based battery was used in most of the commercial EVs in the last decade, especially Ni-MH battery for propulsion. However, this type of BT has significant disadvantages such as poor charge and discharge efficiency, high self-discharge rate, memory effect, and low performance in cold weather (Cluzel and Douglas, 2012). The memory effect of Ni-Cd battery proved to be unsuitable for EV application requiring high charge and discharge rate. In fact, Ni-Cd battery has been banned due to the toxicity of its components (Catenacci et al., 2013). The use of Ni-MH batteries in EV applications has decreased due to negative aspects such as low charging efficiency, very high self-discharge rate of up to 20% per month, long charging times and battery self-discharge when not in use (Yong et al., 2015).

The use of Lithium-based batteries as a battery in EVs has started a new era. Lithium-based battery is one of the promising BTs that accept high energy density, high power density, light weight, cheap, non-toxic and fast charging (Armand and Tarascon, 2008; Wen et al., 2020). The lithium-based battery dominates the newest range of EVs. For example, the Nissan Leaf, Mitsubishi i-MiEV, Tesla Model S and Chevrolet Volt, which are currently the best EV options, use Li-ion battery packs (Catenacci et al., 2013; Cluzel and Douglas, 2012). Several built-in batteries fall under the category of lithium-based batteries such as Li-ion, Lithium-Ion Polymer (Li-Po), and Lithium-Iron Phosphate (LiFePO4). Li-Po battery is developed from Li-ion battery which can be shaped into various sizes for better packaging optimization. LiFePO4 battery provides high power density, greater life cycle and better safety, however, it has lower energy density compared to Li-ion battery. The current lithium-based battery has some limitations, especially where battery failure could lead to a risk of fire and explosion. Current lithium-based BT is not fully mature, however, has the potential to be the perfect rechargeable battery for future EV applications (Yong et al., 2015).

There are some BTs that provide superior performance in the experimental stage. These batteries are Lithium-Sulfur (Li-S), Zinc-Air (Zn-air) and Lithium-Air (Li-air). The Li-S battery has a relatively high energy density in the lithium-based battery category and has a low cost advantage due to the use of cheap sulfur. However, Li-S battery has a high discharge rate and short life cycle (Kolosnitsyn and Karaseva, 2008). Another potential candidate for future EVs is the Zn-air battery. This type of battery has a very high energy density, which is higher than a lithium-based battery. The main disadvantages of current Zn-air battery are low power density and short life cycle. Similarly, the Li-air battery is still in the prototype stage and has not yet been commercialized (Christensen et al., 2011). However, the theoretically high gravity energy density of more than 1700 Wh kg^{-1} enables it to compete with conventional ICEV (Miao et al., 2019). Current research is focused on the development of this attractive BT to expand the full range of electric propulsion in EVs (Yong et al., 2015).

3. MATERIALS AND METHODS

The method used in this thesis, in which heat management is carried out in the battery systems of EVs, is air cooling and heating systems in li-ion batteries.

3.1. Thermal Management Studies

Until this section, detailed information was given on EVs, batteries of EVs and heat management in battery systems of EVs. In the light of this information given in this section, analyzes (simulations) were carried out with CFX, a software of Computational Fluid Dynamics (CFD), in computer environment in order to perform TM of battery systems. With the analysis, it was observed how many degrees and in which regions the maximum temperatures occurred in the battery system. As a result of the observation, many analyzes were performed to bring the thermal performance to the optimum level and the results were revealed.

Ansys CFX is a high performance CFD software tool that provides reliable and fast solutions in a wide variety of CFD and multiphysics applications. CFX is known for its exceptional accuracy, robustness and speed when simulating turbomachinery such as pumps, fans, compressors and gas and hydraulic turbines.

3.2. Introduction To Analysis

In the literature, battery systems are examined in 4 levels. These are: cell level, module level, pack level and system level. The levels are shown in Figure 3.1.;

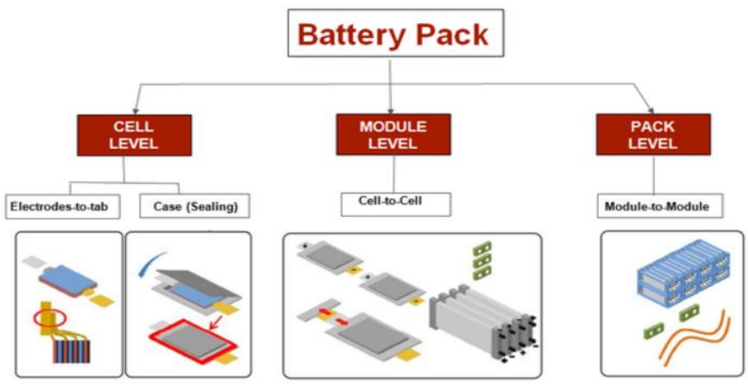


Figure 3.1. Battery system (What is Lithium-Ion Battery Pack?. Retrieved from www.ufo-battery.com)

The number of cells in a battery model and the number of modules in the battery pack vary depending on the expected power from the battery. In this thesis, analyzes have been carried out to examine the heat management in the module-level battery system.

3.3. Module Properties And Geometry

Considering that all kinds of li-ion batteries can be examined in the battery module, a battery cell in super ellipse geometry is used. A battery module containing 25 cells was used in the analyses. Normally, more than 100 cells can be used in a battery module and more than 1000 cells in a battery pack. However, when we look at the literature, it is seen that instead of analyzing with a large number of cells, studies and improvements have been made on heat management in fewer cells. In the literature, this method was preferred for this thesis.

Air cooling method was chosen as the cooling method, since it is an older and easier cooling method than other cooling methods. In the analyzes, the air flow entering the module was modeled within certain intervals, as in other different parameters. This subject will be discussed in the next section.

The cell design of the module-level battery was carried out in the 3D Solid Modeling program. The module design was inspired by Tesla, an EV manufacturer. Figure 3.2 shows the design of the battery module. This design is presented as an example among all designs.

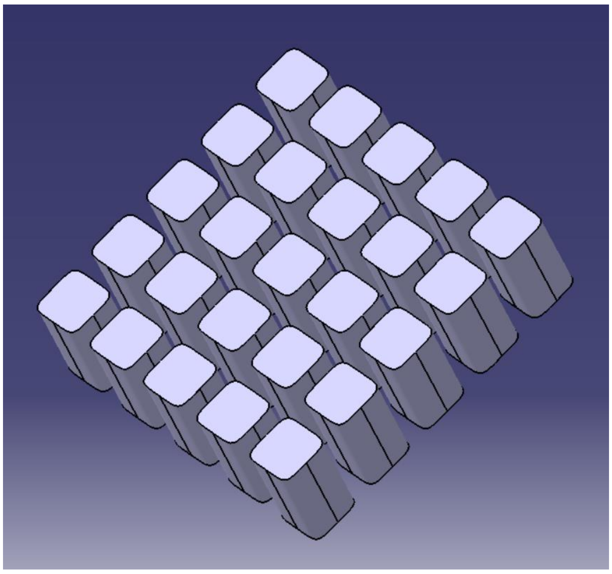


Figure 3.2. Battery module design

3.3.1. Super Ellipse Geometry

The super ellipse equation is a generalized form of the equation of an ellipse. It can generate the shapes of diamonds, ellipses, rectangles, and their transition shapes (Huang et al., 2020). The super ellipse is defined analytically by the formula (Ni, Elishakoff, Jiang, Fu, Han, 2016);

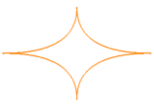
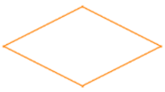
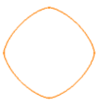
$$\left|\frac{x}{a}\right| + \left|\frac{y}{b}\right| = 1$$

where n, a and b are positive real numbers.

This formula describes a closed curve contained in the rectangle $-a \leq x \leq a$ and $-b \leq y \leq b$. The numbers a and b are referred to as semi-diameters or semi-axes of the super ellipse.

With n = 2, the super ellipse is reduced to an ordinary ellipse ($a \neq b$) or ordinary circle (a = b). When n is greater than 2, super ellipse looks like a rectangle with rounded corners, with zero curvature at points (±a, 0) and (0, ±b). For n between 0 and 1, the super ellipse looks like a four-armed star with concave sides. Specifically, for n = 1 / 2, each of the four arcs represents Quadratic Bézier curve and is a segment of a parabola. When n = 1, the super ellipse reduces to rhombus with corners (±a, 0) and (0, ±b). For 1 < n < 2, the curve looks like a rhombus with convex sides.

Table 3.1. Geometrical spesifications of superellipses in narrow range

n \ b/a	1	2	3	5	10
0,5					
1					
1,5					

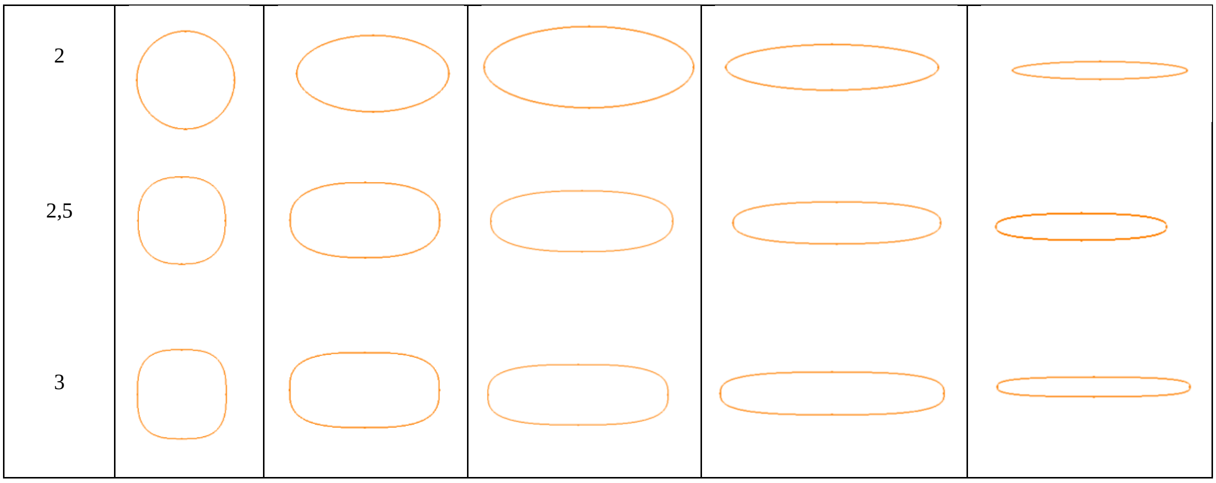


Table 3.1 shows the geometrical spesifications of the superellipse in narrow range in 2D. The purpose of this table is to present changes in geometry within the ranges covered by this study. The following image similarly shows geometrical properties for larger ranges.

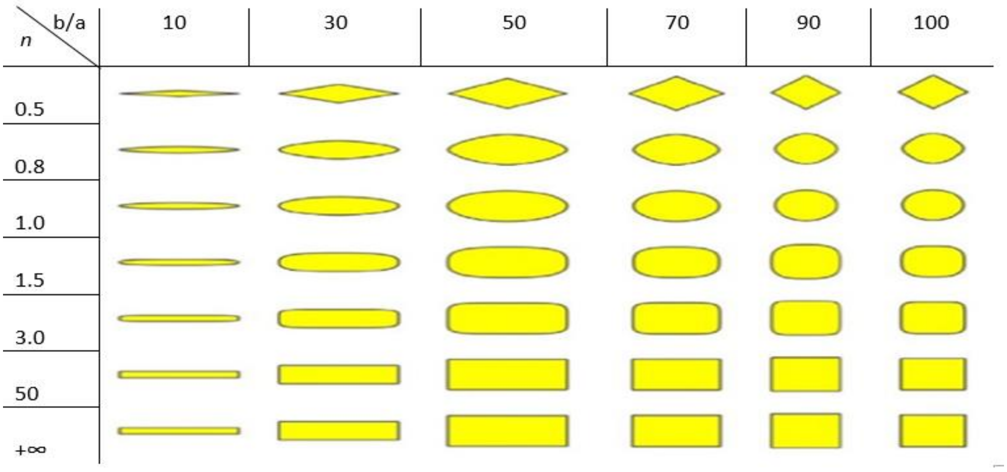


Figure 3.3. Geometrical features of 2D super ellipses with $100 \geq b/a \geq 10$ and $n \geq 0.5$. (Lin, Chen, Liu and Zhang, 2019)

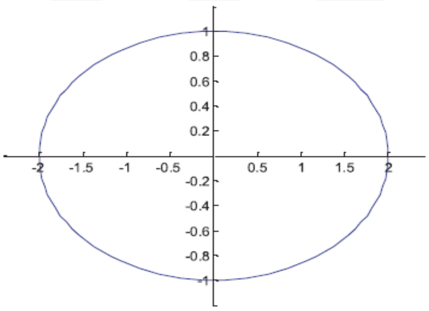
In the equation, the symbols n, a and b represent the deformation coefficient, the semi-axis in the x-axis direction and the semi-axis in the y-axis direction, respectively. Figure 3.4 illustrates the geometrical features of super ellipses with m from 0.5 to + ∞ and a/b from 0.1 to 1.0.
It is shown that the shape of super ellipse will evolve continuously from rhombus, rhombus like, ellipse, rectangle-like to rectangle with the increasing m from 0.5 to + ∞.

The above equation contains two terms, each of these being represented by the expression raised in the same power n . The literature propose to use two different powers, namely m and n to represent more general class of curves, as follows:

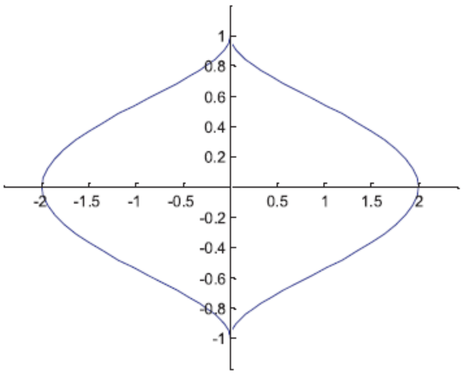
$$\left|\frac{x}{a}\right|^m + \left|\frac{y}{b}\right|^n = 1$$

where m either equals to or differs from n.

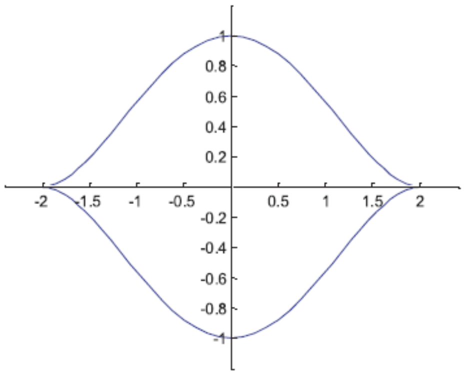
If m = n, one gets the Laméor Hein’s super ellipse. In the general case m ≠ n the curve possesses more flexibility of behavior, and apparently a better possible fit to describe available experimental information. Figure 3.4 shows super ellipse (m = n = 2) and generalized super ellipses (m = 1 / 2 , n = 2 ; m = 2 , n = 1 / 2 ; m = 3 / 4 , n = 2 ; m = 2 , n = 3 / 4) with the semi-diameters set at a = 2 and b = 1 respectively (Ni et al., 2016).



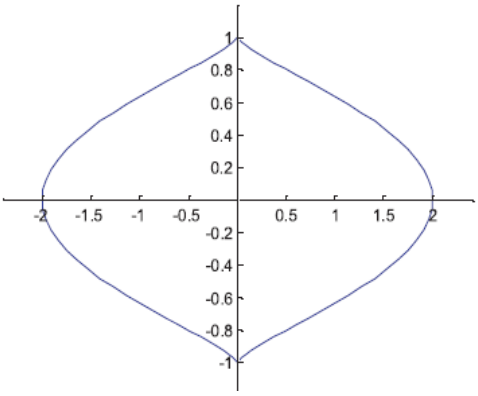
(a) m=n=2



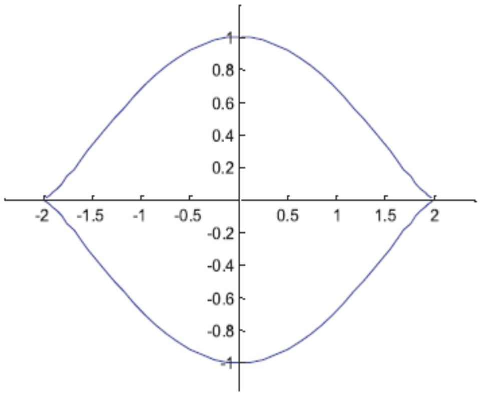
(b) m=1/2, n=2



(c) m=2, n=1/2



(d) m=3/4, n=2



(e) m=2, n=3/4

Figure 3.4. Super ellipse (a) and generalized super ellipses, (b), (c), (d) and (e).

The super ellipse and super ellipsoids were apparently independently uncovered by Hein (1905–1996), Danish mathe- matician, inventor, designer and poet by Wikipedia. Specifically, he popularized its use in architecture, urban planning and furniture making. He designed the roundabout Stockholm's old city square Sergels Torg in the form of super ellipse. (Super Ellipse, Retrieved from www.fact-index.com)

3.3.2. Creating Geometry With Super Ellipse And Geometry Properties

As stated in the Module Properties and Geometry title, the module design was made with 3D Solid Modeling. The basic equation of super ellipse design is written in 3D Solid Modeling as a rule. The design is parametrically designed in order to easily see the changes in the geometry of the determined parameters. The determined parameters are a, b, n given in the equation. In addition to these, other parameters in the study were determined as heat flux Q, cell height h and distance between cells d, inlet air velocity V_{inlet} and inlet air temperature T_{inlet}.

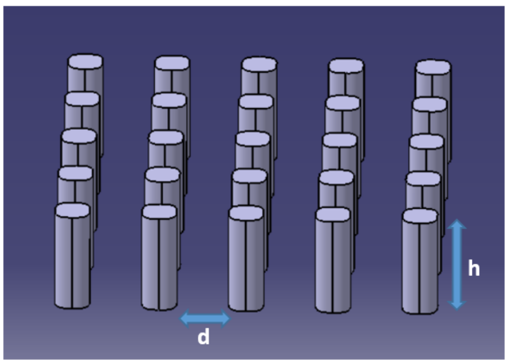


Figure 3.5. Representation of Geometry Parameters d and h

3.3.3. Determination Of Parameter Values And Experiment Design

The parameters to be used in experiment design have been stated in the previous headings. For b and a, the ratio was considered as a single parameter. In this case, there are a total of 7 parameters b / a, n, d, h, Q, V_{inlet}, T_{inlet}. While determining the parameter ranges, the limits were determined by considering the previous studies in the literature. The limits set for these values are shown in the table below:

Table 3.2. Range of Parameters

Parameters	**b/a**	**n**	**d (mm)**	**h (mm)**	**Q (W/m^2)**	**V_{inlet} (m/s)**	**T_{inlet} (°C)**
Range	1 - 10	1 - 3	150 - 300	250 - 400	250 - 500	1 - 7	10 - 60

The first step in experimental design in the study was to define the limits for each parameter. Regression method was used in experimental design. Regression is the opposite of interpolation. To summarize, it is assumed that the values used in interpolation are correct and contain no measurement errors. Therefore, the interpolation polynomial is expressed as a function that passes over points. In regression, the situation reverses. The values used in the regression are considered to be slightly inaccurate and contain measurement errors. In other words, in regression, it is assumed that points scatter around a specific function (Buzzi-Ferraris and Manenti, 2010).

In curve fitting, a function that reflects the distribution character of the points is selected and this function is passed through the middle of all points. Intermediate values are estimated with this function. The process of passing a function through the middle of all points is often called curve fitting (surface fitting in a multivariate case) or Regression. The most important thing in the regression process is to choose the function that will reflect the character of the points (data). Low order polynomial functions are widely used in curve or surface fitting. Regression (curve fitting) is divided into Linear Regression and Nonlinear Regression. The constants of the function (design) to be fitted in linear regression are easily obtained by solving the set of linear equations. In nonlinear regression, the constants of the function (design) are tried to be obtained from the solution of the iterative nonlinear equation set. In nonlinear regression, it is difficult to determine the constants of the design and results may not always be obtained. Therefore, if possible, the Nonlinear Regression problem is solved by transforming variables into a Linear Regression problem.

To make curve or surface fitting easier, a more general method can be developed so that the design constants for any selected polynomial can be easily determined. The parabolic polynomial (design) to be fitted can be written as the product of n- variable parabolic response surface and the constant part, as follows (Yükselen, Retrieved from www.web.itu.edu.tr).

The values of the design at x_1, x_2, x_3, ... , x_n points can be written in matrix form as follows. :

$$\underbrace{\begin{Bmatrix} f_1 \\ f_2 \\ . \\ f_n \end{Bmatrix}}_{F_{mat}} = \underbrace{\begin{bmatrix} 1 & x_1 & y_1 & x_1^2 & y_2^2 & x_1 y_1 \\ 1 & x_2 & y_2 & x_2^2 & y_2^2 & x_1 y_1 \\ . & \dots & \dots & \dots & \dots & \dots \\ . & \dots & \dots & \dots & \dots & \dots \\ 1 & x_n & y_n & x_n^2 & x_n^2 & x_n y_n \end{bmatrix}}_{X_{mat}} \underbrace{\begin{Bmatrix} c_1 \\ c_2 \\ . \\ c_n \end{Bmatrix}}_{C_{mat}} \tag{1}$$

If the vector consisting of real function values is called F_{mat}.

In this case, the sum of squares of the errors at each point is written in matrix form as follows:

$$E = [X_{mat}C_{mat} - F]^T \, [X_{mat}C_{mat} - F] \tag{2}$$

The derivative of error with respect to constants with the application of the least decision method,

$$\frac{\partial E}{\partial C_{mat}} = [X_{mat}]^T \, [X_{mat}C_{mat} - F_{mat}] + [X_{mat}C_{mat} - F_{mat}]^T \, X_{mat} = 0 \tag{3}$$

By editing the above expression, the design constants are found as follows:

$$[X_{mat}C_{mat} - F_{mat}]^T X_{mat} = [X_{mat}]^T([X_{mat}C_{mat} - F_{mat}]^T)^T = [X_{mat}]^T \; [X_{mat}C_{mat} - F_{mat}]$$

$$[X_{mat}]^T \; [X_{mat}C_{mat} - F_{mat}] + [X_{mat}C_{mat} - F_{mat}]^T X_{mat} = 0 \Rightarrow 2[X_{mat}]^T \; [X_{mat}C_{mat} - F_{mat}] = 0 \Rightarrow [X_{mat}]^T X_{mat}C_{mat} = [X_{mat}]^T F_{mat} \Rightarrow$$

$$C_{mat} = \left[X_{mat}{}^T X_{mat}\right]^{-1} X_{mat}{}^T F_{mat} \tag{4}$$

The n-variable parabolic equations were used in this study with 7 parameters, arranged according to 7 variables.

3.3.3.1. D-Optimal Experiment Design

D-optimal designs are experimental designs developed to efficiently produce the response surface design with fewer points. The D-optimal design method is essentially a D-optimal selection method. With the D-optimal design, a brand new experimental design cannot be obtained independently of other experimental designs (Wang, Myers, Smith, & Ye, 2004). The desired number of test points is selected using the D-optimal criterion from the main designs such as the Full Factorial experimental design. It has been widely used in recent years due to its feature of determining the desired number of points.

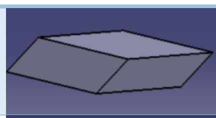
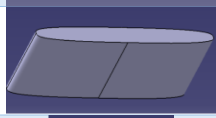
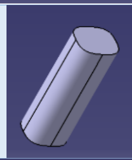
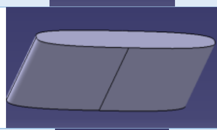
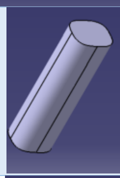
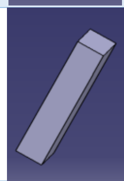
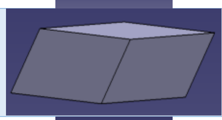
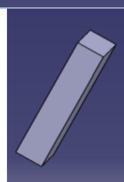
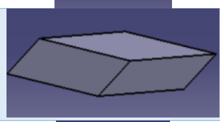
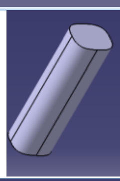
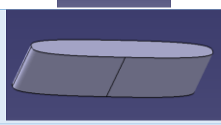
In the general case, there are at least $\frac{(n+1)(n+2)}{2}$ constants to be determined for an n-variable parabolic response surface. According to this formula, since there are 7 different parameters determined in this study, at least 36 must be constant. In our study, 45 designs were determined with MATLAB in order to be more reliable. In Matlab, the minimum, middle, and maximum values are represented by -1, 0, +1, respectively. Also, the code written is as follows:

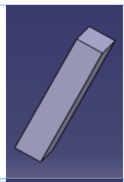
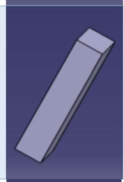
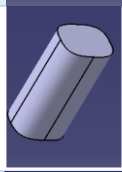
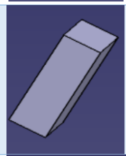
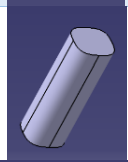
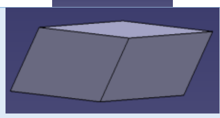
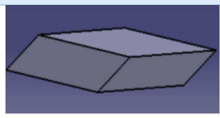
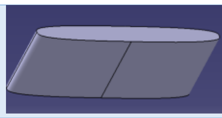
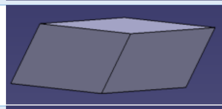
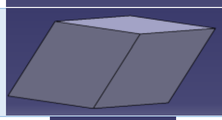
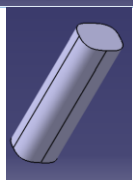
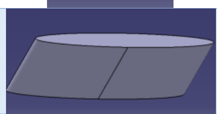
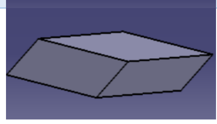
n= number of variables
m= the number of points needed,
q= quadratic (parabolic design)

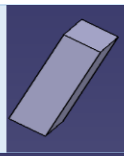
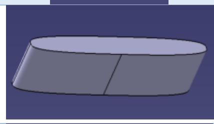
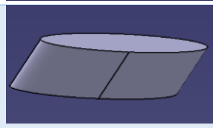
m=(n+1)*(n+2)/2 + 0.2* (n+1)*(n+2)/2 (5)
rowexch(n,m,'q')

If the minimum, middle, maximum points determined according to 45 points are arranged according to the parameter limits, the following table is obtained;

Table 3.3. Minimum, middle, maximum points according to parameter limits

Parameter / Exp. Num.	**b/a**	**n**	**d (mm)**	**h (mm)**	**Q (W/m²)**	**V_{inlet} (m/s)**	**T_{inlet} (°C)**	**Cell Geometry**
1	10	1	300	250	250	7	10	
2	10	3	150	400	500	1	10	
3	1	3	150	325	500	7	10	
4	10	3	300	400	250	1	10	
5	1	3	150	400	250	1	10	
6	1	1	150	400	500	7	10	
7	10	1	300	400	250	1	60	
8	1	1	150	400	500	1	60	
9	10	1	150	250	500	7	10	
10	1	3	300	400	500	7	60	
11	10	3	150	250	500	1	60	

12	1	1	150	400	250	7	60	
13	1	1	225	400	250	1	10	
14	1	3	225	250	250	7	60	
15	1	1	300	250	250	1	10	
16	1	3	150	325	250	1	60	
17	10	1	150	400	250	7	10	
18	10	1	150	250	375	7	60	
19	10	3	300	400	500	1	60	
20	10	1	300	400	500	7	60	
21	5,5	1	300	400	500	4	10	
22	1	3	300	400	250	7	10	
23	10	2	150	400	250	1	60	
24	10	1	300	250	500	1	10	

25	1	1	150	250	500	1	10	
26	10	3	300	250	500	7	10	
27	5,5	2	300	250	500	1	60	
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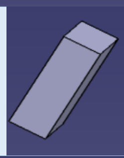
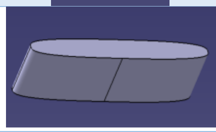
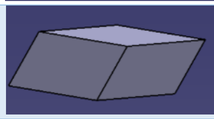
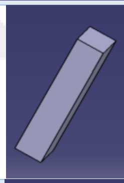
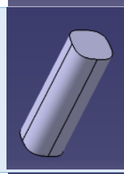
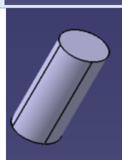
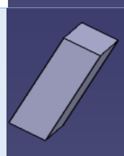
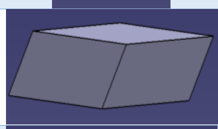
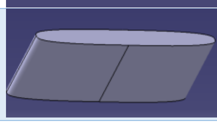
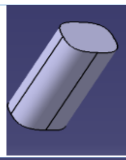
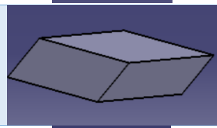
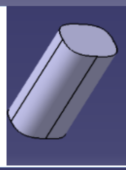
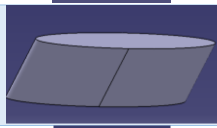
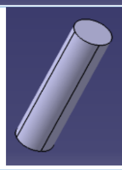
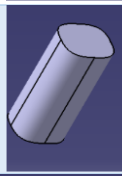
29	1	1	300	250	500	4	60	
30	10	3	300	250	250	7	60	
31	5,5	1	150	250	250	4	35	
32	1	1	300	400	375	1	35	
33	1	3	300	325	500	1	10	
34	1	2	150	250	250	7	10	
35	1	1	300	250	500	7	35	
36	10	1	150	325	375	1	10	
37	10	3	150	400	250	7	60	

38	1	3	150	250	500	7	60	
39	10	1	225	250	250	1	60	
40	1	3	225	250	375	4	10	
41	10	2	300	400	375	7	10	
42	1	2	300	400	250	4	60	
43	1	3	300	250	250	1	35	
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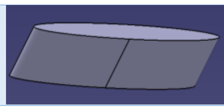
45	10	2	225	325	500	4	35	

3.4. Analysis Input Data

The analysis was done in the CFX module of ANSYS.

3.4.1. Heat Transfer Equations

There are 3 types of heat transfer: heat conduction, convection and radiation.

Heat conduction equations (Fourier's law):

$$q_x'' = -k\,\frac{dT}{dx} \qquad (\mathrm{W/m^2})$$

$$q_x = q_x'' A_c \qquad (\mathrm{W}) \qquad (6\text{-}7)$$

Heat convection equations (Newton's law of cooling):

$q'' = h\,(T_s - T_\infty)$ (W/m^2)

$q = hA_s(T_s - T_\infty)$ (W) (8-9)

Radiation equations:

$E = \varepsilon\sigma T_s{}^4$ (W/m^2)

$\sigma = 5.67 * 10^{-8}$ (W/m^{2}K^4) (10-11)

Energy equations for volume control balance:

$E_{in} + E_g - E_{out} = E_{st}$

$E_{st} = \rho V c_p \frac{dT}{dt}$ (12-13)

Heat equations according to different coordinates can be shown as:

Cartesian coordinate	$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}$
Cylindrical coordinate	$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}$
Spherical coordinate	$\frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2\frac{\partial T}{\partial r}\right) + \frac{1}{r^2 \sin\theta^2}\frac{\partial}{\partial \phi}\left(k\frac{\partial T}{\partial \phi}\right) + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(k\sin\theta\frac{\partial T}{\partial \theta}\right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t}$

(14-15-16)

Calculations based on the study of Ye, Rubel and Li (2019). According to this study, management equations used to solve three dimensional flow problems with time include continuity equation, momentum equation and energy equation.

Continuity equation

$\frac{\partial P}{\partial t} + \nabla.(\rho \mathrm{u}) = 0$ (17)

X-momentum $\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u\mathrm{u}) = -\frac{\partial P}{\partial x} + \nabla.(\mu\nabla u) + S_{M_x}$ (18)

Y-momentum $\frac{\partial(\rho v)}{\partial t} + \nabla.(\rho v\mathrm{u}) = -\frac{\partial P}{\partial y} + \nabla.(\mu\nabla v) + S_{M_y}$ (19)

Z-momentum $\frac{\partial(\rho w)}{\partial t} + \nabla.(\rho w\mathrm{u}) = -\frac{\partial P}{\partial z} + \nabla.(\mu\nabla w) + S_{M_w}$ (20)

Energy equation $mC_p\frac{dT_c}{dt} = \nabla.(\lambda_c\nabla T_c) + Q_g$ (21)

Basically, the main equation required in this study is the energy equation. The equation of state was given in Equations (17)–(21) (Ekmekçi Güçlüten and Tüccar, 2020).

3.4.2. Material Properties

The thermal properties of the cylindrical LiFePO4 battery cell, which is a type of li-ion battery used in the analysis, are shown in Table 3.4. (Zhang,2010).

Table 3.4. Material Properties of Li-Ion Battery

Material Properties	**Value**
Molar Mass (kg/mol)	1.0
Density ($kg \cdot m^{-3}$)	1958.7
Spesific Heat Capacity ($J \cdot kg^{-1} \cdot k^{-1}$)	733
Thermal Conductivity ($W \cdot m^{-1} \cdot k^{-1}$)	2.7

Average values of the cell were used in thermal analysis. The material of the cooling channel used in the battery module is aluminum (Al 6061).

3.4.3. Boundary Conditions

Analyzes have been conducted based on time. The number of iterations is determined as 100 depending on the time. The effect of gravity has been added to the analysis. Gravity is in the –z direction when looking at the coordinate system in the design shown in Figure 3.8.

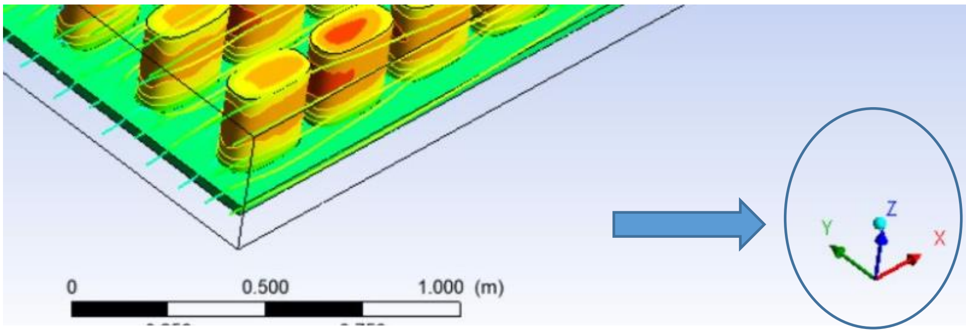


Figure 3.6. Coordinate system in ANSYS

Ambient temperature is defined as 25 °C and inlet air temperature and velocity are defined as variable. Air flow direction is in the same direction in all analyzes and is from +x to -x according to the coordinate system. The variable range is given in the previous headings. Accordingly, the temperature distribution in the cells of the battery module and the resulting maximum temperature were investigated.

3.4.4. Analysis Steps

Ansys Workbench CFX module was used in the study. After the geometry was imported, a plate was designed like a table under the cells, and a ghost box was designed outside the module. In Ansys, this box was assigned as frozen as if it was throwing material. Then the mesh was assigned to the geometry. After the mesh assignment, the inlet and outlet directions of the air were determined as inlet and outlet. The areas on the battery box, other than the inlet and outlet, were designated as walls. Plate is also specified as these regions. Cells were likewise specified and air was assigned as fluid. Some domains were assigned in the setup part of the analysis. These domains are shown in the table below:

Table 3.5. Domain properties of setup part in analysis

Assigned Names	Domain Type	Location	Material	Status
Fluid	Domain	Fluid	Air	Fluid
Cells	Domain	Cells	Li-Ion	Solid
Plate	Domain	Plate	Aluminum	Solid
Heat Source	Subdomain	Cells		

After the domain assignments, the boundaries of the flow were determined as walls. At this point, heat transfer coefficient was added as 7.5 $W.m^{-2}.K^{-1}$ and ambient temperature as 25 °C. The inlet of the flow is limited between the wall starting from the inlet and continuing to the outlet. At this point, relative pressure is added as 0 Pa. In analyzes, the model is meshed before making solutions. The purpose of the mesh operation is to divide the model into physical parts and to perform mathematical operations on it.

The number of iterations was entered as 100 and the necessary command was loaded in order to reach the maximum temperature information in the cells, which is the main purpose of our study.

3.5. Optimization with MATLAB

The general aim of optimization is minimize or maximize a function. The optimization aim of this study is minimize the maximum temperature of the battery cells. Finding the ideal parameter values and minimizing the maximum temperature with optimization ensures that the cells are brought to the ideal operating temperature range. This extends the life of the cells and provides a more efficient thermal management process.

So, the first step of optimization in Matlab is to create a function. For this, our experimental design was loaded into Matlab and a program was written to create a function. The resulting function is given below:

$$\mathbf{T_{max}} = 258.326347 + 0.526379 * (b/a) - 2.988753 * (n) + 0.158234 * (d) + 0.081743 * (h) - 0.009720 * (Q) - 4.042026 * (V_{inlet}) + 0.818809 * (T_{inlet}) - 0.041370 * (b/a) * (b/a) + 0.238976 * (b/a) * (n) - 0.002503 * (b/a) * (d) + 0.000638 * (b/a) * (h) - 0.001077 * (b/a) * (Q) + 0.084759 * (b/a) * (V_{inlet}) + 0.003954 * (b/a) * (T_{inlet}) + 0.898815 * (n) * (n) -0.015158 * (n) * (d) + 0.012674 * (n) * (h) - 0.008660 * (n) * (Q) + 0.452425 * (n) * (V_{inlet}) + 0.008058 * (n) * (T_{inlet}) - 0.000185 * (d) * (d) - 0.000069 * (d) * (h) + 0.000036 * (d) * (Q) - 0.006320 * (d) * (V_{inlet}) - 0.000314 * (d) * (T_{inlet}) - 0.000152 * (h) * (h) - 0.000038 * (h) * (Q) + 0.003702 * (h) * (V_{inlet}) + 0.000515 * (h) * (T_{inlet}) + 0.000053 * (Q) * (Q) - 0.001423 * (Q) * (V_{inlet}) + 0.000029 * (Q) * (T_{inlet}) + 0.307894 * (V_{inlet}) * (V_{inlet}) + 0.009400 * (V_{inlet}) * (T_{inlet}) - 0.000148 * (T_{inlet}) * (T_{inlet})$$

The image comparing the fit and test chart is given below:

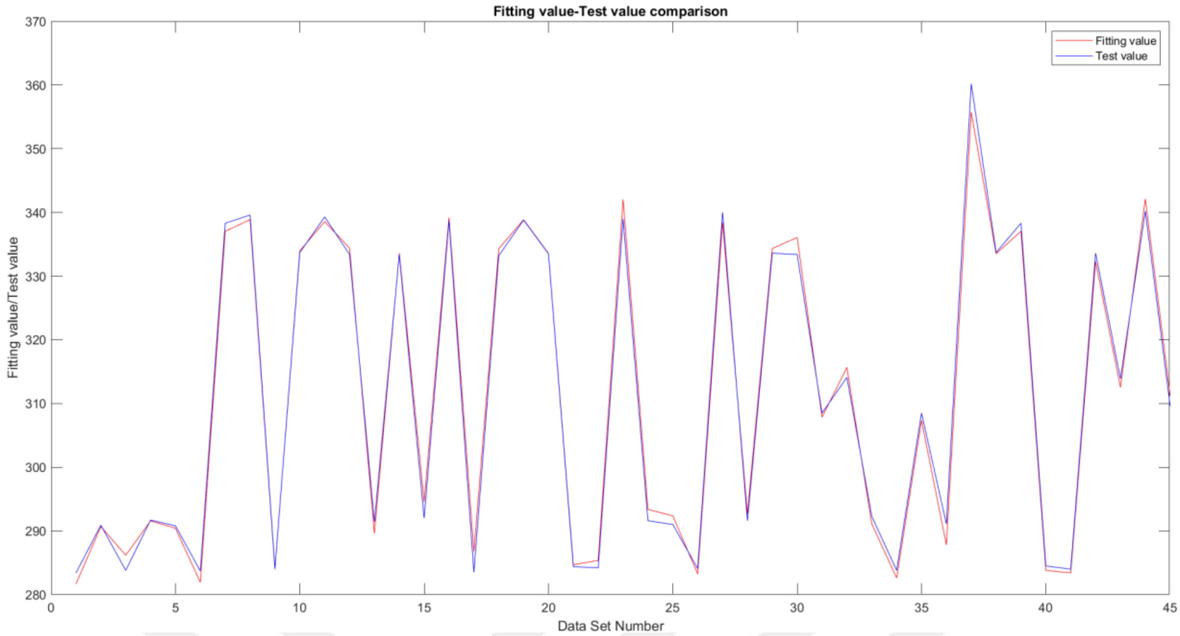


Figure 3.7. Analysis Value – T_{max} Function Comparison

The R^2 value of the created function was found to be 0.995558 according to the experimental design and results. In other words, the accuracy of the function can be interpreted as 99.5%. This is a very high and almost error-free rate.

This function has been optimized by programming in MATLAB. Two different methods, Constraint Function Local Optimization and Genetic Algorithm Method, were used for optimization.

In the Constraint Function Local Optimization Method, limits are determined and the optimum values of the model are sought within these limits. The genetic algorithm can be applied to solve problems that are not well suited for standard optimization algorithms, including problems where the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear. In this study, it is aimed to minimize the maximum temperature in battery cells.

Table 3.6. Maximum and minimum values of each parameter

Parameter	Range
b/a	$1 \ll b/a \ll 10$
n	$1 \ll n \ll 3$

d (mm)	$150 \ll d \ll 300$
h (mm)	$250 \ll h \ll 400$
Q (W/m²)	$250 \ll Q \ll 500$
V_{inlet} (m/s)	$1 \ll V_{inlet} \ll 7$
T_{inlet} (°C)	$10 \ll T_{inlet} \ll 60$

In Constraint Function Local Optimization, it was aimed to reach 3 different optimum values by using the minimum, middle and maximum values of each parameter. Two different alternative solutions were obtained with the Genetic Algorithm. The results obtained in both methods will be examined in the 4th main title.

4. RESULTS AND DISCUSSION

4.1. Analysis Results For Experiment Design

The results of 45 analyzes performed in accordance with the boundary conditions of the specified method are as follows. The results are given in the table according to the parameters and the experimental design.

Table 4.1. Maximum temperature table with parameters

Parameter/ Experiment Number	b/a	n	d	h	Q	V_{inlet}	T_{inlet}	Maximum Temperature (°K)	Maximum Temperature (°C)
Exp 1	10	1	300	250	250	7	10	283,4	10,3
Exp 2	10	3	150	400	500	1	10	290,9	17,8
Exp 3	1	3	150	325	500	7	10	283,8	10,7
Exp 4	10	3	300	400	250	1	10	291,7	18,6
Exp 5	1	3	150	400	250	1	10	290,8	17,7
Exp 6	1	1	150	400	500	7	10	283,7	10,6
Exp 7	10	1	300	400	250	1	60	338,3	65,2
Exp 8	1	1	150	400	500	1	60	339,6	66,5
Exp 9	10	1	150	250	500	7	10	284,1	11
Exp 10	1	3	300	400	500	7	60	333,7	60,6
Exp 11	10	3	150	250	500	1	60	339,3	66,2
Exp 12	1	1	150	400	250	7	60	333,4	60,3
Exp 13	1	1	225	400	250	1	10	291,4	18,3
Exp 14	1	3	225	250	250	7	60	333,4	60,3
Exp 15	1	1	300	250	250	1	10	292	18,9
Exp 16	1	3	150	325	250	1	60	338,7	65,6
Exp 17	10	1	150	400	250	7	10	283,5	10,4
Exp 18	10	1	150	250	375	7	60	333,2	60,1
Exp 19	10	3	300	400	500	1	60	338,8	65,7
Exp 20	10	1	300	400	500	7	60	333,5	60,4

Exp 21	5,5	1	300	400	500	4	10	284,4	11,3
Exp 22	1	3	300	400	250	7	10	284,2	11,1
Exp 23	10	2	150	400	250	1	60	339	65,9
Exp 24	10	1	300	250	500	1	10	291,6	18,5
Exp 25	1	1	150	250	500	1	10	291	17,9
Exp 26	10	3	300	250	500	7	10	284,1	11
Exp 27	5,5	2	300	250	500	1	60	340	66,9
Exp 28	10	3	150	250	250	1	10	291,6	18,5
Exp 29	1	1	300	250	500	4	60	333,6	60,5
Exp 30	10	3	300	250	250	7	60	333,4	60,3
Exp 31	5,5	1	150	250	250	4	35	308,5	35,4
Exp 32	1	1	300	400	375	1	35	314,1	41
Exp 33	1	3	300	325	500	1	10	292,3	19,2
Exp 34	1	2	150	250	250	7	10	283,8	10,7
Exp 35	1	1	300	250	500	7	35	308,5	35,4
Exp 36	10	1	150	325	375	1	10	291,1	18
Exp 37	10	3	150	400	250	7	60	360,2	87,1
Exp 38	1	3	150	250	500	7	60	333,7	60,6
Exp 39	10	1	225	250	250	1	60	338,3	65,2
Exp 40	1	3	225	250	375	4	10	284,5	11,4
Exp 41	10	2	300	400	375	7	10	284	10,9
Exp 42	1	2	300	400	250	4	60	333,6	60,5
Exp 43	1	3	300	250	250	1	35	313,9	40,8
Exp 44	5,5	3	225	400	375	1	60	340,2	67,1
Exp 45	10	2	225	325	500	4	35	309,6	36,5

As seen in the table, 10.3 °C and experiment 1 have the lowest maximum temperature, and 87.1 °K and experiment 37 have the highest maximum temperature.

The temperature distribution images of experiment 1 and experiment 37 with the lowest and highest maximum temperatures in Ansys CFX are given respectively.

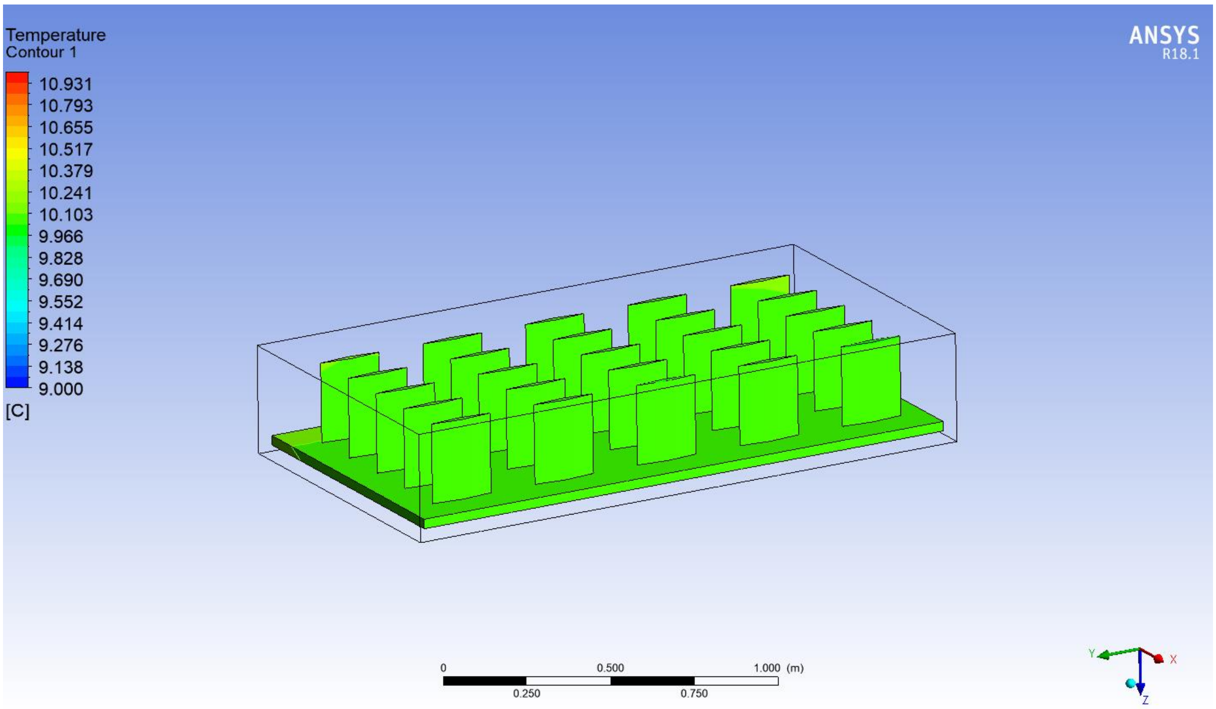


Figure 4.1. Temperature distribution of battery for experiment 1

As seen in Figure 4.1, experiment 1 gave the best result in the whole models. Therefore, no overheating was observed in the cells.

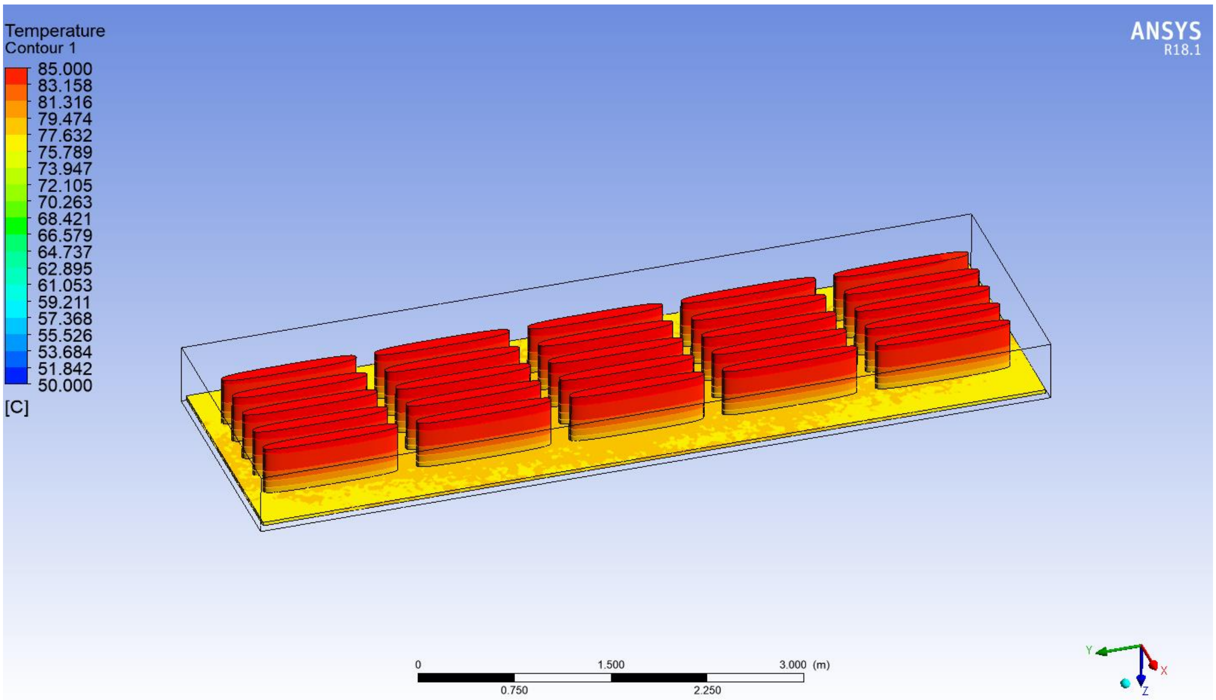


Figure 4.2. Temperature distribution of battery for experiment 37

Figure 4.2 shows the temperature distribution for experiment 37 with the highest maximum temperature level in the entire experimental design. Accordingly, overheating was observed in the cells and it was concluded that thermal management was insufficient. Parameter values for Experiment 1 and 37;

Table 4.2. Comparison of parameters of best and worst results

Parameters/ Experiment No	**b/a**	**n**	**d (mm)**	**h (mm)**	**Q (W/m^2)**	**V_{inlet} (m/s)**	**T_{inlet} (°C)**
Experiment 1	10	1	300	250	250	7	10
Experiment 37	10	3	150	400	250	7	60

When the two results were compared, it was seen that besides the geometric changes in the parameters, the temperature of the air, height of cell and distance between cells had a great effect.

4.2. Optimization Results

The comparison table of the results of ANSYS CFX analysis according to the optimization results and the optimum values found is given.

Table 4.3. Comparison of optimization and ansys results

Optimization Method	**Solution**	**Design Result (°K)**	**Design Result (°C)**	**Ansys Result (°K)**	**Ansys Result (°C)**
Local Optimization	Alternative 1	280.3597	7.21	280.7	7.55
	Alternative 2	280.3167	7.17	283.1	9.95
	Alternative 3	280.4627	7.32	282.9	9.75
Genetic Algorithm	Alternative 1	280.3597	7.21	280.7	7.55
	Alternative 2	280.1300	6.98	283.0	9.85

Optimization results will be examined in detail under two separate headings as Constraint Function Local Optimization and Genetic Algorithm Optimization Results.

4.2.1. Constraint Function Local Optimization Results

Optimum values were obtained as 3 alternative by using the minimum, middle and maximum values of the parameters in local optimization. According to this;

a) Alternative 1

Optimum values obtained using minimum values for each parameter respectively;

Parameters = (b/a), (n), (d), (h), (Q), (V_{inlet}), (T_{inlet})
Optimum Values = (1.0000), (1.0000), (150.0000), (250.0000), (303.7726), (6.2775), (10.0000)

The geometric design created according to optimum values;

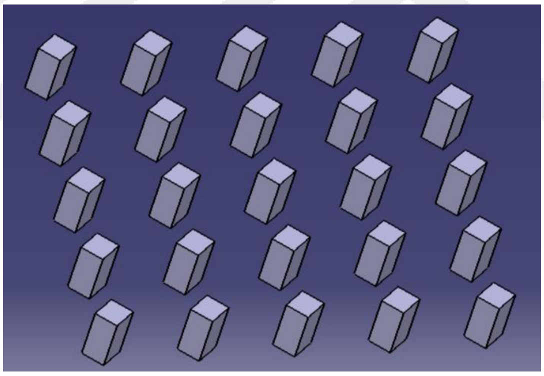


Figure 4.3. Geometry design of alternative 1 of constraint function local optimization

The value found for the T_{max} minimized according to these values;
$(T_{max})_{min}$ 7.21°C

According to analysis results, the maximum temperature was found 7.55 °C. The temperature distribution of optimum values in Ansys;

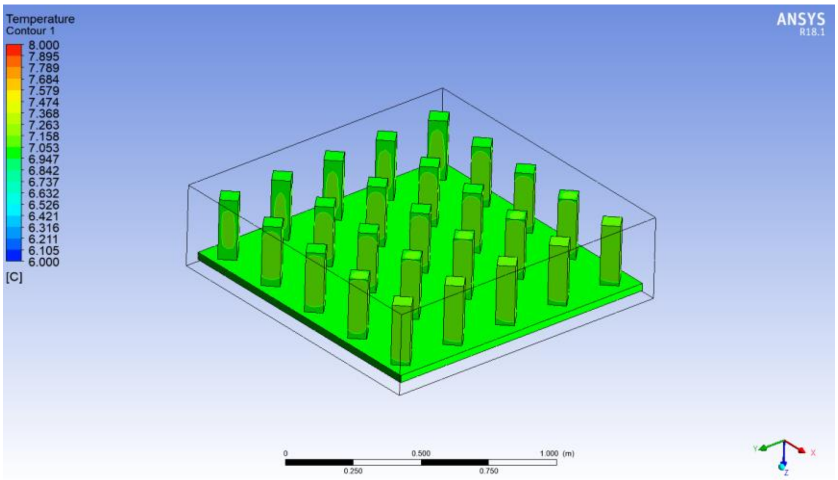


Figure 4.4. Temperature distribution of alternative 1 of constraint function local optimization

Looking at Figure 4.4, it was seen that no overheating was observed in the cells in the module. When analyzed parametrically, it can be interpreted that the inlet air temperature and velocity are sufficient according to the geometry.

b) Alternative 2

Optimum values obtained using middle values for each parameter respectively;

Parameters = (b/a), (n), (d), (h), (Q), (V_{inlet}), (T_{inlet})

Optimum Values = (1.0000), (1.0000), (300.0000), (400.0000), (315.5288), (6.9424), (10.0000)

The geometric design created according to optimum values;

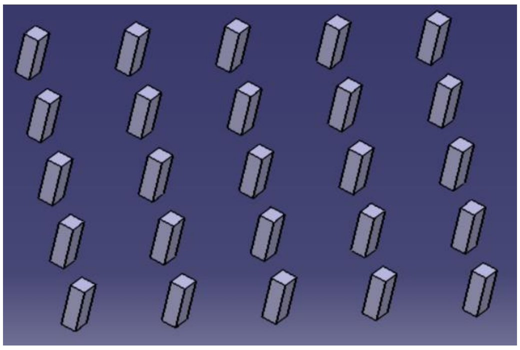


Figure 4.5. Geometry design of alternative 2 of constraint function local optimization

The value found for the T_{max} minimized according to these values;

$(T_{max})_{min}$ = 7.17 °C

According to analysis results, the maximum temperature was found 9.95 °C. The temperature distribution of optimum values in Ansys;

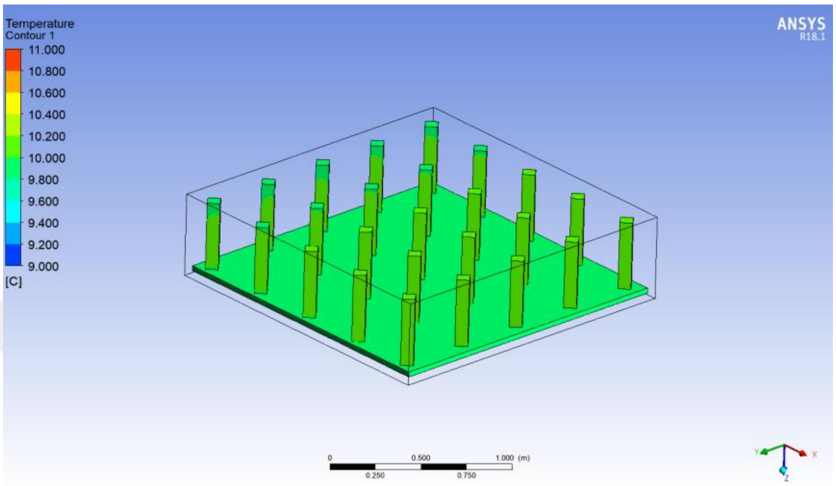


Figure 4.6. Temperature distribution of alternative 2 of constraint function local optimization

Similarly, looking at Figure 4.6, it was seen that no overheating was observed in the cells in the module. When analyzed parametrically, it can be interpreted that the inlet air temperature and velocity are sufficient according to the geometry.

c) Alternative 3

Optimum values obtained using maksimum values for each parameter respectively;

Parameters = (b/a), (n), (d), (h), (Q), (V_{inlet}), (T_{inlet})

Optimum Values= (10.0000), (1.0000), (300.0000), (399.9999), (392.7371), (5.882), (10.0000)

The geometric design created according to optimum values;

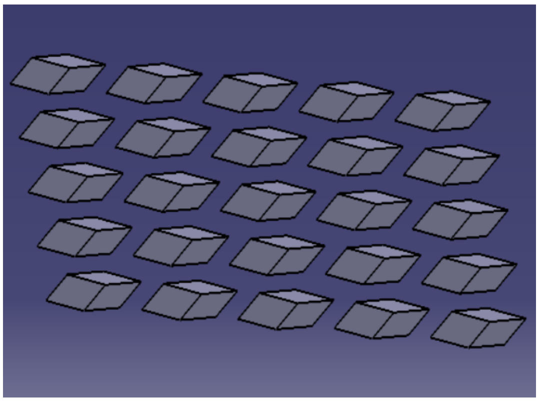


Figure 4.7. Geometry design of alternative 3 of constraint function local optimization

The value found for the T_{max} minimized according to these values;

$(T_{max})_{min}$ = 7.32 °C

According to analysis results, the maximum temperature was found 9.75 °C. The temperature distribution of optimum values in Ansys;

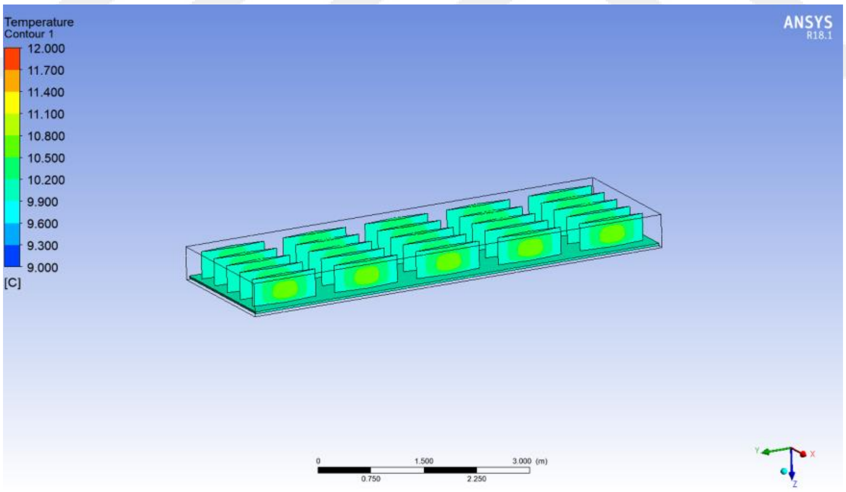


Figure 4.8. Temperature distribution of alternative 3 of constraint function local optimization

Likewise, looking at Figure 4.8, it was seen that no overheating was observed in the cells in the module. When analyzed parametrically, it can be interpreted that the inlet air temperature and velocity are sufficient according to the geometry.

4.2.2. Genetic Algorithm Optimization Results

As an alternative to constraint function local optimization in Matlab, an optimization was also performed with genetic algorithm. In this optimization, two different optimum values were obtained. These optimum values were obtained by using n=1000 population size in the Genetic Algorithm program.

a) Alternative 1

Parameters = (b/a), (n), (d), (h), (Q), (V_{inlet}), (T_{inlet})
Optimum Values = (1.0000), (1.0000), (150.0000), (250.0000), (303.7725), (6.2775), (10.0000)

The value found for the T_{max} minimized according to these values;
$(T_{max})_{min}$ 7.21 °C

The optimum values in the first alternative of the genetic algorithm optimization are the same as the values in the first alternative of the constraint function local optimization. For this reason, both the 3D flow modeling image and the ansys temperature distribution image will be the same with this alternative.

b) Alternative 2

Parameters = (b/a), (n), (d), (h), (Q), (V_{inlet}), (T_{inlet})
Optimum Values = (1.0000), (2.2448), (300.0000), (250.0000), (364.2262), (7.0000), (10.0000)

The value found for the T_{max} minimized according to these values;
$(T_{max})_{min}$ 6.98 °C

The geometric design created according to optimum values;

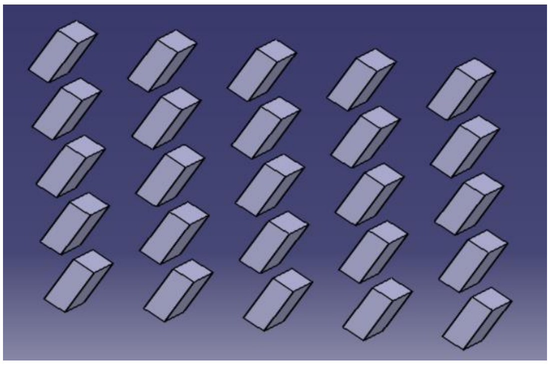


Figure 4.9. Geometry design of alternative 2 of genetic algorithm optimization

According to analysis results, the maximum temperature was found 9.85 °C. The temperature distribution of optimum values in Ansys;

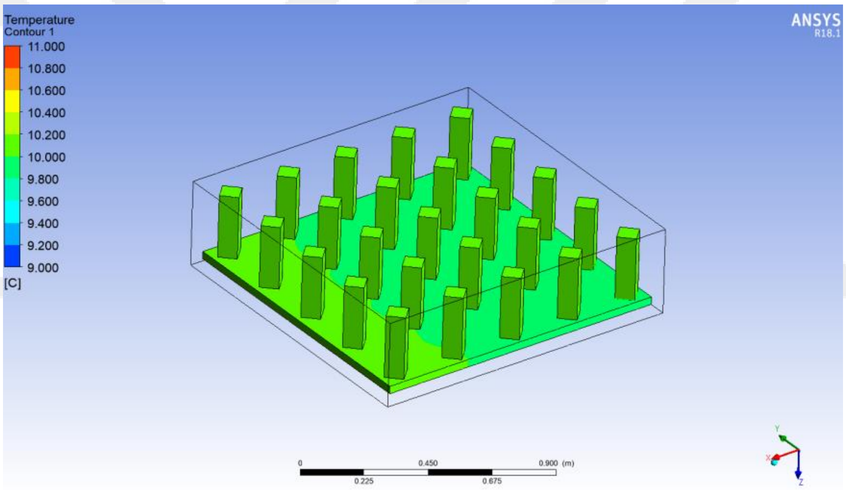


Figure 4.10. Temperature distribution of alternative 2 of genetic algorithm optimization

In all analysis results, it was concluded that the cells showed a temperature distribution suitable for the ideal operating range and no overheating was observed. Therefore, it can be interpreted that the minimization is successful.

However, when looking at the analysis results with the optimization values, it was seen that the Tmax values of alternative 1 of constraint function local optimization and alternative 1 of genetic algorithm optimization were far below the ideal working range. For this reason, other optimization alternatives were found to be more suitable.

5. CONCLUSION AND RECOMMENDATIONS

Since it is thought and planned that the use of EVs will become widespread in the future of the automotive industry, the performance of the battery pack, which is the power source of EVs, is of great importance. The electrical power supplied by the battery pack is affected by many factors. One of these factors is thermal properties. In the literature, the ideal operating temperature range of the battery is stated as approximately 10-60 °C. Temperatures below 10 °C and above 60 °C negatively affect both operating performance and cycle life as they negatively affect battery materials. However, considering both the operating performance and the cycle life parameters, it is desirable that the ideal operating temperature of the battery in a wider range, chosen between 10-60 °C. This value should be taken into account when cooling or heating the battery. The studies carried out in the thesis study include the design of the battery system and the design and finite element analysis of the battery system to provide these values. In this study, the battery module was designed first. The design based on super elliptical geometry was parametrically completed via 3D solid modeling. Based on some parameters determined in the study, it was requested to examine the thermal performance of the system. These parameters are; mathematical determination of super ellipse b/a, likewise n, distance between cells d, cell height h, heat flux Q, air inlet velocity V_{inlet} and air inlet temperatıre T_{inlet}. Limits have been set for these parameters. Multiple analysis can be made according to 7 different parameters. For this reason, experimental design was done with MATLAB. D-Optimal experimental design method was used as an experimental design. 45 designs were created in MATLAB. Then, analyzes were conducted to verify the module design and to determine the thermal performance of the system within the framework of the experimental design. As a result of these desings, analyzes were completed with the CFX module in ANSYS. Air cooling was used as the cooling method. The ambient temperature was determined as 25 °C. The cells were chosen as li-ion batteries. The maximum temperature values in the module were taken into account in the analysis.

In order to verify the study, optimization study was performed in MATLAB according to the 45 results obtained. For this, firstly, a function was created according to our experimental design and its results. At this point, each parameter was considered to be a dimension. The R^2 value for the obtained function was found to be 99.5%. In other words, it can be interpreted that the function created according to the design and its results is 99.5% compatible.

Optimization was carried out with 2 different methods in MATLAB, constraint function local optimization and genetic algorithm optimization. In constraint function local optimization, 3 different alternatives were created as initial values. These were chosen as the minimum, middle and maximum values in the value ranges of the parameters. According to these initial options, 3 different optimum values were found for the parameters and they were minimized by optimization. It was found as 7.21, 7.17 and 7.32 °C, respectively. According to the optimum values found, the optimization was compared with the finite element analysis CFX. With CFX, values of 7.55, 9.95 and 9.75 °C were found, respectively. It can be said that there is a deviation in the second and third. However, compared to the whole experimental design, it has been concluded that the results of the obtained optimum values are minimized in all cases and give better results. In the second method, genetic algorithm optimization, 2 alternatives were obtained by using n=1000 population size. According to the new optimum parameters obtained in these alternatives, 2 more minimized values were found. The first was found to be the same as in the minimal alternative of constraint function local optimization. Therefore, the result will again be 7.21 °C. Considering that the value obtained in the optimization is 7.55 °C, it can be said that it is a completely successful study. The second is minimized to 6.98 °C by optimization. In the analysis with CFX, 9.85 °C was found. Again, there is a deviation. However, the minimization effort has been successful in any case.

As a result of all these studies in this research, it has been seen that the shape, inlet air velocity and temperature have a significant impact on the battery and cell temperature according to the determined parameters and parameter ranges.

In addition to this study, by increasing the level of the battery system, studies can be conducted on the battery pack or the TM of the comprehensive battery system, not the battery module, and different design methods, different parameters and different limits can be determined. In addition, these studies can be verified with experimental studies and applications. Similarly, the effect of parameters on the maximum cell temperature can be investigated with different limits for the same parameters. In another way, the effect of different parameters on the maximum cell temperature can be investigated. As the number of experiments increases, studies can be expanded with different design or optimization methods and can guide future studies. By determining the ideal geometry and keeping it constant, different parameters can be evaluated in the same geometry. Thus, it can be useful in development and improvement by identifying weak points. Or, by increasing the data set with the same parameters, ideal geometry and inputs can be searched with machine learning.

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APPENDIX

BatteryData;

10	1	300	250	250	7	10	283.4
10	3	150	400	500	1	10	290.9
1	3	150	325	500	7	10	283.8
10	3	300	400	250	1	10	291.7
1	3	150	400	250	1	10	290.8
1	1	150	400	500	7	10	283.7
10	1	300	400	250	1	60	338.3
1	1	150	400	500	1	60	339.6
10	1	150	250	500	7	10	284.1
1	3	300	400	500	7	60	333.7
10	3	150	250	500	1	60	339.3
1	1	150	400	250	7	60	333.4
1	1	225	400	250	1	10	291.4
1	3	225	250	250	7	60	333.4
1	1	300	250	250	1	10	292
1	3	150	325	250	1	60	338.7
10	1	150	400	250	7	10	283.5
10	1	150	250	375	7	60	333.2
10	3	300	400	500	1	60	338.8
10	1	300	400	500	7	60	333.5
5.5	1	300	400	500	4	10	284.4
1	3	300	400	250	7	10	284.2
10	2	150	400	250	1	60	339
10	1	300	250	500	1	10	291.6
1	1	150	250	500	1	10	291
10	3	300	250	500	7	10	284.1
5.5	2	300	250	500	1	60	340
10	3	150	250	250	1	10	291.6
1	1	300	250	500	4	60	333.6
10	3	300	250	250	7	60	333.4
5.5	1	150	250	250	4	35	308.5
1	1	300	400	375	1	35	314.1
1	3	300	325	500	1	10	292.3
1	2	150	250	250	7	10	283.8
1	1	300	250	500	7	35	308.5
10	1	150	325	375	1	10	291.1
10	3	150	400	250	7	60	360.2
1	3	150	250	500	7	60	333.7
10	1	225	250	250	1	60	338.3
1	3	225	250	375	4	10	284.5
10	2	300	400	375	7	10	284
1	2	300	400	250	4	60	333.6
1	3	300	250	250	1	35	313.9
5.5	3	225	400	375	1	60	340.2
10	2	225	325	500	4	35	309.6

Battery_con;

```
function [c,ceq]=battery_con(x)
ceq=[] ;
c=[];
```

Battery_obj;

```
function f=battery_obj(x)

f=258.326347+0.526379*x(1)-2.988753*x(2)+0.158234*x(3)+0.081743*x(4)-
0.009720*x(5) 4.042026*x(6)+0.818809*x(7)-
0.041370*x(1)*x(1)+0.238976*x(1)*x(2)
0.002503*x(1)*x(3)+0.000638*x(1)*x(4)-
0.001077*x(1)*x(5)+0.084759*x(1)*x(6)+0.003954*x(1)*x(7)+0.898815*x(2)*x(2)
0.015158*x(2)*x(3)+0.012674*x(2)*x(4)
0.008660*x(2)*x(5)+0.452425*x(2)*x(6)+0.008058*x(2)*x(7)-0.000185*x(3)*x(3)
0.000069*x(3)*x(4)+0.000036*x(3)*x(5)-0.006320*x(3)*x(6)-
0.000314*x(3)*x(7)-0.000152*x(4)*x(4)
0.000038*x(4)*x(5)+0.003702*x(4)*x(6)+0.000515*x(4)*x(7)+0.000053*x(5)*x(5)
0.001423*x(5)*x(6)+0.000029*x(5)*x(7)+0.307894*x(6)*x(6)+0.009400*x(6)*x(7)
0.000148*x(7)*x(7);
f
```

ResponseSurfaceProgram_GozdeEkmekci;

```
function ResponseSurfaceProgram_GozdeEkmekci

% Program: RESPONSE SURFACE METHODOLOGY implementation
% This program creates Polynomial Response Surface
% global BETA ModelOrder ModelType NumVar
% ==================                 USER INPUT
=======================

% Enter Number of Variables, Train Data Sets and Check Data Sets

NumVar=7;
NumTrainSet=45;
NumCheckSet=1;

VariableOrder=size(NumVar,1);
% Select the ORDER of Polynomial Response Surface by Model Order
% ModelOrder=1 : "Linear",   ModelOrder=2 : "Parabolic",
% ModelOrder=3 : "Cubic",    ModelOrder=4 : "4th order",
% ModelOrder=5 : "5th order",  ModelOrder=6 : "6th order"
% ModelOrder=7 : "7th order",  ModelOrder=8 : "8th order",
% ModelOrder=9 : "9th order",  ModelOrder=10 : "10th order"
VariableOrder(1)=2;
VariableOrder(2)=2;
VariableOrder(3)=2;
VariableOrder(4)=2;
VariableOrder(5)=2;
VariableOrder(6)=2;
VariableOrder(7)=2;


ResponseNumber=1;

ReciprocalFlag=[0 0 0 0 0 0 0];  % Reciprocal Flag (0= No Reciprocal, 1=Yes
Reciprocal)
ModelType=1;       %  ModelType=1 (Polynomial),   ModelType=2 (Logarithmic)
Backpress=0;       %  0=Do not use Backward Press elimination (BPRESS),
1=Use BPRESS,


% Enter Check points to measure the accuracy of the RS approximation
%  Check Set 1
```

```
CSET(1,1)=10;
CSET(1,2)=2 ;
CSET(1,3)=225;
CSET(1,4)=325;
CSET(1,5)=500;
CSET(1,6)=4;
CSET(1,7)=35;

CVALUE(1)=309.6;

% =========================        END OF USER INPUT
======================

ModelOrder=max(VariableOrder);

%[ReciprocalRow,ReciprocalColumn]=size(ReciprocalFlag);

ReciprocalRow=size(ReciprocalFlag,1);
ReciprocalColumn=size(ReciprocalFlag,2);

if ReciprocalColumn ~= NumVar
    error('ReciprocalFlag Vector Size should be equal to number of
variables. Check ReciprocalFlag=[] ???');
end

% Calculate the number of terms needed for fitting

    % linear response surface model
        NUM=1;
        for i=1:NumVar
           NUM=NUM+1;
        end

    % quadratic response surface model

        for i=1:NumVar
           if VariableOrder(i)>=2
                for j=i:NumVar
                    if VariableOrder(j)>=2
                        NUM=NUM+1;
                    end

    % cubic response surface model

        for i=1:NumVar
           if VariableOrder(i)>=3
               for j=i:NumVar
                   if VariableOrder(j)>=3
                       for k=j:NumVar
                           if VariableOrder(k)>=3
                               NUM=NUM+1;
                           end

    % 4 th order response surface model

        for i=1:NumVar
            if VariableOrder(i)>=4
                for j=i:NumVar
                    if VariableOrder(j)>=4
                        for k=j:NumVar
```

```
                              if VariableOrder(k)>=4
                                   for l=k:NumVar
                                        if VariableOrder(l)>=4
                                             NUM=NUM+1;
                                        end

    % 5 th order response surface model

        for i=1:NumVar
            if VariableOrder(i)>=5
                  for j=i:NumVar
                      if VariableOrder(j)>=5
                          for k=j:NumVar
                             if VariableOrder(k)>=5
                                  for l=k:NumVar
                                      if VariableOrder(l)>=5
                                          for m=l:NumVar
                                               if VariableOrder(m)>=5
                                                   NUM=NUM+1;
                                               end

    % 6 th order response surface model

   for i=1:NumVar
       if VariableOrder(i)>=6
           for j=i:NumVar
              if VariableOrder(j)>=6
                  for k=j:NumVar
                      if VariableOrder(k)>=6
                          for l=k:NumVar
                              if VariableOrder(l)>=6
                                  for m=l:NumVar
                                      if VariableOrder(m)>=6
                                          for n=m:NumVar
                                              if VariableOrder(n)>=6
                                                  NUM=NUM+1;
                                              end

    % 7 th order response surface model

        for i=1:NumVar
           if VariableOrder(i)>=7
              for j=i:NumVar
                  if VariableOrder(j)>=7
                     for k=j:NumVar
                         if VariableOrder(k)>=7
                             for l=k:NumVar
                                if VariableOrder(l)>=7
                                    for m=l:NumVar
                                        if VariableOrder(m)>=7
                                               for n=m:NumVar
                                                  if VariableOrder(n)>=7
                                                      for o=n:NumVar
                                                          if
VariableOrder(o)>=7
                                                              NUM=NUM+1;
                                                          end

    % 8 th order response surface model
```

```
    for i=1:NumVar
       if VariableOrder(i)>=8
           for j=i:NumVar
               if VariableOrder(j)>=8
                  for k=j:NumVar
                     if VariableOrder(k)>=8
                         for l=k:NumVar
                             if VariableOrder(l)>=8
                                 for m=l:NumVar
                                    if VariableOrder(m)>=8
                                       for n=m:NumVar
                                           if VariableOrder(n)>=8
                                              for o=n:NumVar
                                                 if VariableOrder(o)>=8
                                                     for p=o:NumVar
                                                         if
VariableOrder(p)>=8
                                                             NUM=NUM+1;
                                                         end

    % 9 th order response surface model

     for i=1:NumVar
        if VariableOrder(i)>=9
            for j=i:NumVar
                if VariableOrder(j)>=9
                   for k=j:NumVar
                       if VariableOrder(k)>=9
                          for l=k:NumVar
                              if VariableOrder(l)>=9
                                  for m=l:NumVar
                                      if VariableOrder(m)>=9
                                          for n=m:NumVar
                                              if VariableOrder(n)>=9
                                                 for o=n:NumVar
                                                     if VariableOrder(o)>=9
                                                        for p=o:NumVar
                                                            if
VariableOrder(p)>=9
                                                               for
q=p:NumVar
                                                                  if
VariableOrder(q)>=9

NUM=NUM+1;
                                                                  end


    % 10 th order response surface model

 for i=1:NumVar
    if VariableOrder(i)>=10
        for j=i:NumVar
           if VariableOrder(j)>=10
               for k=j:NumVar
                   if VariableOrder(k)>=10
                       for l=k:NumVar
                           if VariableOrder(l)>=10
                               for m=l:NumVar
                                  if VariableOrder(m)>=10
```

```
                                                        for n=m:NumVar
                                                            if VariableOrder(n)>=10
                                                                for o=n:NumVar
                                                                    if VariableOrder(o)>=10
                                                                        for p=o:NumVar
                                                                            if
VariableOrder(p)>=10
                                                                                for q=p:NumVar
                                                                                    if
VariableOrder(q)>=10
                                                                                        for
r=q:NumVar
                                                                                            if
VariableOrder(r)>=10

NUM=NUM+1;
                                                                                            end

NumTerm=NUM;
NumTermNeeded=NumTerm;

fprintf('Number of Data Set Needed is :%i\n\n',NumTermNeeded)

if ModelOrder>10
    error('Maximum order allowed for rs model has been exceeded!!!');
end

% Read DESIGN DATA (TRAINING DATA) from File (DesignData.m)

    file1 = fopen('BatteryData.m','r');
       if (file1==-1)
           error('ERROR: cannot find file (BatteryData.m) for reading
???');
       end

       counter=0;
       read_complete = 0;

       while (read_complete == 0)
            line=fgets(file1);

            if (line ~= -1)
            [Row,NumColumn]=sscanf(line,'%f');
            counter=counter+1;
            else
                 read_complete=1;
        end
    fclose(file1);
    DesignPointNumber=counter;
    NumTrainSet=DesignPointNumber;

    TVALUE=zeros(NumTrainSet,1) ;

     % Read BETA values from the file line by line
     file1 = fopen('BatteryaData.m','r');
       counter=0;
       read_complete = 0;

       while (read_complete == 0)
            line=fgets(file1);
```

```
            if (line ~= -1)
            [Row,NumColumn]=sscanf(line,'%f');
            counter=counter+1;

            for i=1:NumVar
                 TSET(counter,i)=Row(i);
            end
            TVALUE(counter)=Row(NumVar+ResponseNumber);

            else
                 read_complete=1;
        end
    fclose(file1);

% end of DATA SET reading

TSET
TVALUE

if NumTrainSet<NumTerm
    error('Data is insufficient to create the model!!!');
end

if ModelType==1
   for i=1:NumTrainSet
      for j=1:NumVar
         if ReciprocalFlag(j)==1
            if  TSET(i,j)==0
                error('Reciprocal of zero Training value can lead to
infinity!!!');
            else
                TSET(i,j)=1/TSET(i,j);
            end
CSET

   for i=1:NumCheckSet
      for j=1:NumVar
         if ReciprocalFlag(j)==1
            if  CSET(i,j)==0
                error('Reciprocal of zero Check value can lead to
infinity!!!');
            else
                CSET(i,j)=1/CSET(i,j);
            end

if ModelType==2
    for i=1:NumTrainSet
         if TVALUE(i)<=0
           error('Negative or zero Training value can not be used with
logarithmic scale!!!');
         else
            TVALUE(i)=log(TVALUE(i));
         end

         for j=1:NumVar
            if TSET(i,j)<=0
               error('Negative or zero Training variable can not be used
with logarithmic scale!!!');
            else
```

```
               TSET(i,j)=log(TSET(i,j));
            end
    for i=1:NumCheckSet
         for j=1:NumVar
            if CSET(i,j)<=0
               error('Negative Check variable can not be used with
logarithmic scale!!!');
            else
               CSET(i,j)=log(CSET(i,j));
            end

%  ########################################################################
%           Start of  MODEL ORDER CHANGES WITH VARIABLE ORDER
%  ########################################################################

for i=1:NumTrainSet
    TCOEFF(i,1)=1;
end

for NS=1:NumTrainSet
    for i=1:NumVar
        X(i)=TSET(NS,i);
    end

    % linear response surface model

        NUM=1;
        for i=1:NumVar
           NUM=NUM+1;
           TCOEFF(NS,NUM)=X(i);
        end

    % quadratic response surface model

        for i=1:NumVar
           if VariableOrder(i)>=2
                for j=i:NumVar
                    if VariableOrder(j)>=2
                        NUM=NUM+1;
                        TCOEFF(NS,NUM)=X(i)*X(j);
                    end

    % cubic response surface model

        for i=1:NumVar
           if VariableOrder(i)>=3
               for j=i:NumVar
                   if VariableOrder(j)>=3
                       for k=j:NumVar
                           if VariableOrder(k)>=3
                               NUM=NUM+1;
                               TCOEFF(NS,NUM)=X(i)*X(j)*X(k);
                           end

    % 4 th order response surface model

        for i=1:NumVar
            if VariableOrder(i)>=4
                for j=i:NumVar
                    if VariableOrder(j)>=4
```

```
                            for k=j:NumVar
                                if VariableOrder(k)>=4
                                     for l=k:NumVar
                                          if VariableOrder(l)>=4
                                               NUM=NUM+1;

TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l);
                                          end

    % 5 th order response surface model

        for i=1:NumVar
            if VariableOrder(i)>=5
                  for j=i:NumVar
                      if VariableOrder(j)>=5
                          for k=j:NumVar
                             if VariableOrder(k)>=5
                                  for l=k:NumVar
                                      if VariableOrder(l)>=5
                                          for m=l:NumVar
                                               if VariableOrder(m)>=5
                                                   NUM=NUM+1;

TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l)*X(m);
                                               end

    % 6 th order response surface model

   for i=1:NumVar
       if VariableOrder(i)>=6
           for j=i:NumVar
              if VariableOrder(j)>=6
                  for k=j:NumVar
                      if VariableOrder(k)>=6
                          for l=k:NumVar
                              if VariableOrder(l)>=6
                                  for m=l:NumVar
                                      if VariableOrder(m)>=6
                                          for n=m:NumVar
                                              if VariableOrder(n)>=6
                                                  NUM=NUM+1;

TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l)*X(m)*X(n);
                                              end

    % 7 th order response surface model

        for i=1:NumVar
           if VariableOrder(i)>=7
              for j=i:NumVar
                  if VariableOrder(j)>=7
                     for k=j:NumVar
                         if VariableOrder(k)>=7
                             for l=k:NumVar
                                if VariableOrder(l)>=7
                                    for m=l:NumVar
                                        if VariableOrder(m)>=7
                                               for n=m:NumVar
                                                  if VariableOrder(n)>=7
                                                      for o=n:NumVar
```

```
                                                          if
VariableOrder(o)>=7
                                                              NUM=NUM+1;

TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l)...

*X(m)*X(n)*X(o);
                                                          end

    % 8 th order response surface model

    for i=1:NumVar
       if VariableOrder(i)>=8
           for j=i:NumVar
               if VariableOrder(j)>=8
                  for k=j:NumVar
                     if VariableOrder(k)>=8
                         for l=k:NumVar
                             if VariableOrder(l)>=8
                                 for m=l:NumVar
                                    if VariableOrder(m)>=8
                                       for n=m:NumVar
                                           if VariableOrder(n)>=8
                                              for o=n:NumVar
                                                 if VariableOrder(o)>=8
                                                     for p=o:NumVar
                                                         if
VariableOrder(p)>=8
                                                             NUM=NUM+1;

TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l)...

*X(m)*X(n)*X(o)*X(p);
                                                         end

    % 9 th order response surface model

     for i=1:NumVar
        if VariableOrder(i)>=9
            for j=i:NumVar
                if VariableOrder(j)>=9
                   for k=j:NumVar
                       if VariableOrder(k)>=9
                          for l=k:NumVar
                              if VariableOrder(l)>=9
                                  for m=l:NumVar
                                      if VariableOrder(m)>=9
                                          for n=m:NumVar
                                              if VariableOrder(n)>=9
                                                 for o=n:NumVar
                                                     if VariableOrder(o)>=9
                                                        for p=o:NumVar
                                                            if
VariableOrder(p)>=9
                                                               for
q=p:NumVar
                                                                  if
VariableOrder(q)>=9

NUM=NUM+1;
```

```
TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l)...

*X(m)*X(n)*X(o)*X(p)*X(q);
                                                                  end

    % 10 th order response surface model

 for i=1:NumVar
    if VariableOrder(i)>=10
        for j=i:NumVar
           if VariableOrder(j)>=10
               for k=j:NumVar
                   if VariableOrder(k)>=10
                       for l=k:NumVar
                           if VariableOrder(l)>=10
                               for m=l:NumVar
                                  if VariableOrder(m)>=10
                                       for n=m:NumVar
                                           if VariableOrder(n)>=10
                                              for o=n:NumVar
                                                 if VariableOrder(o)>=10
                                                     for p=o:NumVar
                                                        if
VariableOrder(p)>=10
                                                           for q=p:NumVar
                                                               if
VariableOrder(q)>=10
                                                                   for
r=q:NumVar
                                                                       if
VariableOrder(r)>=10

NUM=NUM+1;

TCOEFF(NS,NUM)=X(i)*X(j)*X(k)*X(l)...

*X(m)*X(n)*X(o)*X(p)*X(q)*X(r);
                                                                       end

end  % end of NS=1:NumTrainSet
%  #########################################################################
%          end of MODEL ORDER CHANGES WITH VARIABLE ORDER
%  #########################################################################

if Backpress==0

[BETA,R2Train,RMStrain,maxTdeviate,maxTrainError]=fitting(TVALUE,NumTrainSe
t,NumTerm,...
    TCOEFF,ModelType);
else

[BETA,RMStrain,maxTdeviate,maxTrainError,NumTermLeft]=backwardpress(TVALUE,
...
    NumTrainSet,NumTerm,TCOEFF,ModelType);
end

file2 = fopen('BETAValues.m','w');
fprintf(file2,'%f ',BETA);
fclose(file2);
```

```
[Tapprox,TrainRMSfit,Termax,maxTerrorIndex,Tmaxdeviate,maxTdeviateIndex]=..
.
AccuracyCalculation(TSET,TVALUE,BETA,NumTrainSet,NumVar,VariableOrder,Model
Type);

[Capprox,CheckRMSfit,Cermax,maxCerrorIndex,Cmaxdeviate,maxCdeviateIndex]=..
.
AccuracyCalculation(CSET,CVALUE,BETA,NumCheckSet,NumVar,VariableOrder,Model
Type);

RecFlag=0;
for i=1:NumVar
    if ReciprocalFlag(i)==1
       RecFlag=1;
       break;
    end

% Print Results to the screen
fprintf('------------------------------------------------------\n');
fprintf('------------------------------------------------------\n');
fprintf('             RESPONSE SURFACE RESULTS              \n');
fprintf('------------------------------------------------------\n');
fprintf('------------------------------------------------------\n\n\n');

if ModelType==1
    if RecFlag==0
       fprintf('Model Type is: POLYNOMIAL\n');
    else
       fprintf('Model Type is: RECIPROCAL POLYNOMIAL\n');
    end
else
    fprintf('Model Type is: LOGARITHMIC\n');
end

switch ModelOrder
   case 1,
      fprintf('Model Order is: Linear\n\n');
   case 2,
      fprintf('Model Order is: Parabolic\n\n');
   case 3,
      fprintf('Model Order is: Cubic\n\n');
   case 4,
      fprintf('Model Order is: 4th order\n\n');
   case 5,
      fprintf('Model Order is: 5th order\n\n');
   case 6,
      fprintf('Model Order is: 6th order\n\n');
   case 7,
      fprintf('Model Order is: 7th order\n\n');
   case 8,
      fprintf('Model Order is: 8th order\n\n');
   case 9,
      fprintf('Model Order is: 9th order\n\n');
   case 10,
      fprintf('Model Order is: 10th order\n\n');
   otherwise,
      fprintf('Very High order selected. Check or change the model
order!!!\n\n');
end
```

```
fprintf('\n');
fprintf('Number of TRAIN Set= %i\n',NumTrainSet);
fprintf('Number of CHECK Set= %i\n',NumCheckSet);

fprintf('\n\n');

fprintf('\n\n');
fprintf('Set#   TrainApproximate   TrainTest\n');
fprintf('-----  ----------------   ----------\n');

for i=1:NumTrainSet
   fprintf('%i   %f   %f \n', i, Tapprox(i), TVALUE(i));
end

fprintf('\n\n');

fprintf('Set#   CheckApproximate   CheckTest\n');
fprintf('-----  ----------------  ----------\n');

for i=1:NumCheckSet
   fprintf('%i   %f   %f \n', i, Capprox(i), CVALUE(i));
end

fprintf('\n\n');

fprintf('TrainData R2 value = %f \n',R2Train);

fprintf('\n\n');

fprintf('TrainRMSfit  CheckRMSfit\n');
fprintf('-----------  ------------\n');
fprintf('%f      %f \n', TrainRMSfit, CheckRMSfit);

fprintf('\n\n');

fprintf('MaxTrainDeviation  MaxCheckDeviation\n');
fprintf('-----------------  ------------------\n');
fprintf('%f          %f \n', Tmaxdeviate, Cmaxdeviate);

fprintf('\n\n');

fprintf('MaxTrainDeviateIndex  MaxCheckDeviateIndex\n');
fprintf('---------------------  ------------------\n');
fprintf('%i                %i \n', maxTdeviateIndex, maxCdeviateIndex);

fprintf('\n\n');

fprintf('MaxTrainError(Percent)  MaxCheckError(Percent) \n');
fprintf('-------------  ----------------\n');
fprintf('%f             %f \n', 100*Termax, 100*Cermax);

fprintf('\n\n');

fprintf('MaxTrainErrorIndex  MaxCheckErrorIndex \n');
fprintf('------------------  ------------------\n');
fprintf('%i                   %i \n',maxTerrorIndex, maxCerrorIndex);

if Backpress==1
    fprintf('\n\n');
```

```
    fprintf('BACKWARD PRESS elimination used\n');
    fprintf('Number of Initial model constants is: %i\n',NumTerm);
    fprintf('Number of model constants after BACKWARD PRESS is: %i',...
    NumTermLeft);
end

fprintf('\n\n\n');

fprintf('TrainData R2 value = %f \n',R2Train);
fprintf('\n');

%
***************************************************************************
% Print Results to the File: "ResponseSurfaceResults.m"
file1 = fopen('ResponseSurfaceResults.m','w');
fprintf(file1,'-----------------------------------------------------\n');
fprintf(file1,'-----------------------------------------------------\n');
fprintf(file1,'             RESPONSE SURFACE RESULTS              \n');
fprintf(file1,'-----------------------------------------------------\n');
fprintf(file1,'-----------------------------------------------------
\n\n\n');

if ModelType==1
    if RecFlag==0
       fprintf(file1,'Model Type is: POLYNOMIAL\n');
    else
       fprintf(file1,'Model Type is: RECIPROCAL POLYNOMIAL\n');
    end
else
    fprintf(file1,'Model Type is: LOGARITHMIC\n');
end

switch ModelOrder
   case 1,
      fprintf(file1,'Model Order is: Linear\n\n');
   case 2,
      fprintf(file1,'Model Order is: Parabolic\n\n');
   case 3,
      fprintf(file1,'Model Order is: Cubic\n\n');
   case 4,
      fprintf(file1,'Model Order is: 4th order\n\n');
   case 5,
      fprintf(file1,'Model Order is: 5th order\n\n');
   case 6,
      fprintf(file1,'Model Order is: 6th order\n\n');
   case 7,
      fprintf(file1,'Model Order is: 7th order\n\n');
   case 8,
      fprintf(file1,'Model Order is: 8th order\n\n');
   case 9,
      fprintf(file1,'Model Order is: 9th order\n\n');
   case 10
      fprintf(file1,'Model Order is: 10th order\n\n');
   otherwise,
      fprintf(file1,'Very High order selected. Check or change the model
order!!!\n\n');
end

fprintf(file1,'\n');
fprintf(file1,'Number of TRAIN Set= %i\n',NumTrainSet);
```

```
fprintf(file1,'Number of CHECK Set= %i\n',NumCheckSet);

fprintf(file1,'\n\n');
fprintf(file1,'Set#   TrainApproximate   TrainTest\n');
fprintf(file1,'-----  ----------------   ----------\n');

for i=1:NumTrainSet
   fprintf(file1,'%i   %f   %f \n', i, Tapprox(i), TVALUE(i));
end

fprintf(file1,'\n\n');

fprintf(file1,'Set#   CheckApproximate   CheckTest\n');
fprintf(file1,'-----  ----------------  ----------\n');

for i=1:NumCheckSet
   fprintf(file1,'%i   %f   %f \n', i, Capprox(i), CVALUE(i));
end

fprintf(file1,'\n\n');

fprintf(file1,'TrainData R2 value = %f \n',R2Train);

fprintf(file1,'\n\n');

fprintf(file1,'TrainRMSfit  CheckRMSfit\n');
fprintf(file1,'-----------  -----------\n');
fprintf(file1,'%f      %f \n', TrainRMSfit, CheckRMSfit);

fprintf(file1,'\n\n');

fprintf(file1,'MaxTrainDeviation  MaxCheckDeviation\n');
fprintf(file1,'-----------------  -----------------\n');
fprintf(file1,'%f          %f \n', Tmaxdeviate, Cmaxdeviate);

fprintf(file1,'\n\n');

fprintf(file1,'MaxTrainDeviateIndex  MaxCheckDeviateIndex\n');
fprintf(file1,'--------------------  -----------------\n');
fprintf(file1,'%i                %i \n', maxTdeviateIndex,
maxCdeviateIndex);

fprintf(file1,'\n\n');

fprintf(file1,'MaxTrainError(Percent)  MaxCheckError(Percent) \n');
fprintf(file1,'-------------  ---------------\n');
fprintf(file1,'%f             %f \n', 100*Termax, 100*Cermax);

fprintf(file1,'\n\n');

fprintf(file1,'MaxTrainError  MaxCheckError \n');
fprintf(file1,'------------------  -----------------\n');
fprintf(file1,'%i                   %i \n',maxTerrorIndex, maxCerrorIndex);

if Backpress==1
    fprintf(file1,'\n\n');
    fprintf(file1,'BACKWARD PRESS elimination used\n');
    fprintf(file1,'Number of Initial model constants is: %i\n',NumTerm);
    fprintf(file1,'Number of model constants after BACKWARD PRESS is:
%i',...
```

```
    NumTermLeft);
end

fprintf(file1,'\n\n\n');

fprintf(file1,'TrainData R2 value = %f \n',R2Train);

fprintf(file1,'\n');

% PRINT RESPONSE SURFACE MODEL
PrintModel(file1,BETA,NumVar,VariableOrder,ModelType);

% PLOT
for i=1:NumTrainSet
   Datanum(i)=i;
end

plot(Datanum,Tapprox,'r',Datanum,TVALUE,'b');
title('Fitting value-Test value comparison') ;
xlabel('Data Set Number') ;
ylabel('Fitting value/Test value') ;
legend('Fitting value','Test value');

fclose(file1);

%===========================================================================
function [BETA,R2,RMS,EMAX,MAXPERC]=fitting(FVALUE,NPOINT,n,XMAT,ModelType)
% ========================================================================
%                 Calculate Root Mean Squared Fitting Error
% ========================================================================

XT=zeros(n,NPOINT);
BETA=zeros(n,1);
A=zeros(n,n);
B=zeros(n,1);
ERMAXF=zeros(NPOINT,1);
PCENTERROR=zeros(NPOINT,1);
SRMSF=zeros(NPOINT,1);

XT=XMAT';
A=XT*XMAT;
B=XT*FVALUE;

% Gauss Elimination
BETA=A\B;

for I=1:NPOINT
    SUMF=0.0;
    for J=1:n
        SUMF=SUMF+XMAT(I,J)*BETA(J);
    end
    if ModelType==2
       FVALUE(I)=exp(FVALUE(I));
       SUMF=exp(SUMF);
    end
    ERMAXF(I)=abs(FVALUE(I)-SUMF);
    PCENTERROR(I)=abs((SUMF-FVALUE(I))/FVALUE(I));
    SRMSF(I)=(FVALUE(I)-SUMF)^2;
end
```

```
SUMFVALUE=0;
for i=1:NPOINT
    SUMFVALUE=SUMFVALUE+FVALUE(i);
end
AVEFVALUE=SUMFVALUE/NPOINT;

E2MODEL=0;
E2FVALUEAVE=0;
for i=1:NPOINT
    E2MODEL=E2MODEL+SRMSF(i);
    E2FVALUEAVE=E2FVALUEAVE+(FVALUE(i)-AVEFVALUE)^2 ;
end

R2=(E2FVALUEAVE-E2MODEL)/E2FVALUEAVE ;

% Maximum deviation between Approximate and Exact values
EMAX=ERMAXF(1);
for I=2:NPOINT
   if ERMAXF(I)>EMAX
      EMAX=ERMAXF(I);
   end
end

% Maximum Error percent
MAXPERC=PCENTERROR(1);
for I=2:NPOINT
   if PCENTERROR(I)>MAXPERC
      MAXPERC=PCENTERROR(I);
   end
end

% Root Mean Square (RMS) fitting error
RMS=0.0;
for I=1:NPOINT
   RMS=RMS+SRMSF(I);
end
RMS=RMS/NPOINT;
RMS=sqrt(RMS);

%=========================================================================
function [fapprox,fRMSfit,maxFerror,maxFerrorIndex,maxFdeviate,...
         maxFdeviateIndex]=AccuracyCalculation(SET,FVALUE,BETA,NumSet,...
         NumVar,VariableOrder,ModelType)

% Calculate Accuracy Error at Check Set Points

for NS=1:NumSet
    for i=1:NumVar
        X(i)=SET(NS,i);
    end

    % linear response surface model
    fvalue=BETA(1);
    NUM=1;
    for i=1:NumVar
       NUM=NUM+1;
       fvalue=fvalue+BETA(NUM)*X(i);
    end

    % quadratic response surface model
```

```
        for i=1:NumVar
            if VariableOrder(i)>=2
                 for j=i:NumVar
                     if VariableOrder(j)>=2
                         NUM=NUM+1;
                         fvalue=fvalue+BETA(NUM)*X(i)*X(j);
                     end

     % cubic response surface model
        for i=1:NumVar
            if VariableOrder(i)>=3
                for j=i:NumVar
                    if VariableOrder(j)>=3
                        for k=j:NumVar
                            if VariableOrder(k)>=3
                                NUM=NUM+1;
                                fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k);
                            end

     % 4 th order response surface model

         for i=1:NumVar
             if VariableOrder(i)>=4
                 for j=i:NumVar
                     if VariableOrder(j)>=4
                         for k=j:NumVar
                             if VariableOrder(k)>=4
                                  for l=k:NumVar
                                       if VariableOrder(l)>=4
                                            NUM=NUM+1;

fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l);
                                       end

     % 5 th order response surface model

         for i=1:NumVar
             if VariableOrder(i)>=5
                   for j=i:NumVar
                       if VariableOrder(j)>=5
                           for k=j:NumVar
                              if VariableOrder(k)>=5
                                  for l=k:NumVar
                                      if VariableOrder(l)>=5
                                          for m=l:NumVar
                                               if VariableOrder(m)>=5
                                                   NUM=NUM+1;

fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l)*X(m);
                                               end

     % 6 th order response surface model
     for i=1:NumVar
        if VariableOrder(i)>=6
            for j=i:NumVar
               if VariableOrder(j)>=6
                   for k=j:NumVar
                       if VariableOrder(k)>=6
                           for l=k:NumVar
```

```
                              if VariableOrder(l)>=6
                                  for m=l:NumVar
                                      if VariableOrder(m)>=6
                                          for n=m:NumVar
                                              if VariableOrder(n)>=6
                                                  NUM=NUM+1;

fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l)...
                                                  *X(m)*X(n);
                                              end

    % 7 th order response surface model

        for i=1:NumVar
           if VariableOrder(i)>=7
              for j=i:NumVar
                  if VariableOrder(j)>=7
                     for k=j:NumVar
                         if VariableOrder(k)>=7
                             for l=k:NumVar
                                if VariableOrder(l)>=7
                                    for m=l:NumVar
                                        if VariableOrder(m)>=7
                                               for n=m:NumVar
                                                  if VariableOrder(n)>=7
                                                      for o=n:NumVar
                                                          if
VariableOrder(o)>=7
                                                              NUM=NUM+1;

fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l)...

*X(m)*X(n)*X(o);
                                                          end

    % 8 th order response surface model

    for i=1:NumVar
       if VariableOrder(i)>=8
           for j=i:NumVar
               if VariableOrder(j)>=8
                  for k=j:NumVar
                     if VariableOrder(k)>=8
                         for l=k:NumVar
                             if VariableOrder(l)>=8
                                 for m=l:NumVar
                                    if VariableOrder(m)>=8
                                       for n=m:NumVar
                                           if VariableOrder(n)>=8
                                              for o=n:NumVar
                                                 if VariableOrder(o)>=8
                                                     for p=o:NumVar
                                                         if
VariableOrder(p)>=8
                                                             NUM=NUM+1;

fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)...

*X(l)*X(m)*X(n)*X(o)*X(p);
                                                         end
```

```
% 9 th order response surface model

 for i=1:NumVar
    if VariableOrder(i)>=9
        for j=i:NumVar
            if VariableOrder(j)>=9
               for k=j:NumVar
                   if VariableOrder(k)>=9
                      for l=k:NumVar
                          if VariableOrder(l)>=9
                              for m=l:NumVar
                                  if VariableOrder(m)>=9
                                      for n=m:NumVar
                                          if VariableOrder(n)>=9
                                             for o=n:NumVar
                                                 if VariableOrder(o)>=9
                                                    for p=o:NumVar
                                                        if
VariableOrder(p)>=9
                                                            for
q=p:NumVar
                                                               if
VariableOrder(q)>=9
NUM=NUM+1;
fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)...
*X(l)*X(m)*X(n)*X(o)*X(p)*X(q);
                                                               end

    % 10 th order response surface model

 for i=1:NumVar
    if VariableOrder(i)>=10
        for j=i:NumVar
           if VariableOrder(j)>=10
               for k=j:NumVar
                   if VariableOrder(k)>=10
                       for l=k:NumVar
                           if VariableOrder(l)>=10
                               for m=l:NumVar
                                  if VariableOrder(m)>=10
                                       for n=m:NumVar
                                           if VariableOrder(n)>=10
                                              for o=n:NumVar
                                                 if VariableOrder(o)>=10
                                                     for p=o:NumVar
                                                        if
VariableOrder(p)>=10
                                                           for q=p:NumVar
                                                               if
VariableOrder(q)>=10
                                                                   for
r=q:NumVar
                                                                       if
VariableOrder(r)>=10
                                                      NUM=NUM+1;
```

```
fvalue=fvalue+BETA(NUM)*X(i)*X(j)...

*X(k)*X(l)*X(m)*X(n)*X(o)*X(p)...
                                                                      *X(q)*X(r);
                                                                                     end

    if ModelType==2
       fvalue=exp(fvalue);
    end

    fapprox(NS)=fvalue;
    fdeviate(NS)=abs(fapprox(NS)-FVALUE(NS));
    ferror(NS)=abs((fapprox(NS)-FVALUE(NS))/FVALUE(NS));
end

[maxFerror,maxFerrorIndex]=max(ferror);
[maxFdeviate,maxFdeviateIndex]=max(fdeviate);

fRMSfit=0.0;
for i=1:NumSet
   fRMSfit=fRMSfit+(fapprox(i)-FVALUE(i))^2;
end
fRMSfit=fRMSfit/NumSet;
fRMSfit=sqrt(fRMSfit);

%============================================================================
function
[BETF,RMS,EMAX,MAXPERC,NumTermLeft]=backwardpress(FVALUE,NPOINT,NTERM,XMAT,
ModelType)

BETAF=zeros(NTERM+1,NTERM);
% XMAT=zeros(NPOINT,NTERM);
BETF=zeros(NTERM,1);
% BETA=zeros(NTERM);
BXOLD=zeros(NPOINT,NTERM);
BXX=zeros(NTERM+1,NPOINT,NTERM);
IXFLAG=zeros(NTERM,1);
IKOUNT=zeros(NTERM,1);
% FVALUE=zeros(NPOINT);
RMSF=zeros(NTERM+1,1);
EMAXF=zeros(NTERM+1,1);
MAXPERCF=zeros(NTERM+1,1);

n=NTERM;

NUM=1;
for i=1:NPOINT
    for j=1:n
        BXOLD(i,j)=XMAT(i,j);
        BXX(NUM,i,j)=XMAT(i,j);
%         BX(i,j)=XMAT(i,j);
     end
end

[BETA,RMS,EMAX,MAXPERC]=fitting(FVALUE,NPOINT,n,XMAT,ModelType);

for i=1:n
    BETAF(NUM,i)=BETA(i);
end
```

```
EMAXF(NUM)=EMAX;
MAXPERCF(NUM)=MAXPERC;
RMSF(NUM)=RMS;

KNTER=0;

% ----------------------------------------------------------- C
while NTERM>1
     for KK=n:-1:2
         NUM=NUM+1;

         BX=zeros(NPOINT,n-1);

         for i=1:NPOINT
            for j=1:n-1
               if j>=KK
                  BXX(NUM,i,j)=BXOLD(i,j+1);
               else
                  BXX(NUM,i,j)=BXOLD(i,j);
               end
               BX(i,j)=BXX(NUM,i,j);
            end
         end

         [BETA,RMS,EMAX,MAXPERC]=fitting(FVALUE,NPOINT,n-1,BX,ModelType);

         for i=1:n-1
            BETAF(NUM,i)=BETA(i);
         end

         EMAXF(NUM)=EMAX;
         MAXPERCF(NUM)=MAXPERC;
         RMSF(NUM)=RMS;
     end

     ARSMIN=RMSF(1);
     KID=1;

     for i=2:NUM
         if RMSF(i)<ARSMIN
            ARSMIN=RMSF(i);
            KID=i;
         else
            ARSMIN=ARSMIN;
         end
     end

     KNTER=KNTER+1;

     if (KID==1)||(n==2)
         break;
     end

     for i=1:NPOINT
        for j=1:n-1
           BXOLD(i,j)=BXX(KID,i,j);
           BXX(1,i,j)=BXOLD(i,j);
        end
     end
```

```
     for i=1:n-1
         BETAF(1,i)=BETAF(KID,i);
         RMSF(1)=RMSF(KID);
     end

     n=n-1;
     NUM=1;
end
% --------------------------------------------------------------- C

     EMAX=EMAXF(KID);
     MAXPERC=MAXPERCF(KID);
     RMS=RMSF(KID);

     for K=1:NTERM
         for j=1:n
             IKOUNT(j)=1;
             for i=1:NPOINT
                if abs(XMAT(i,K)-BXX(KID,i,j))>0.001*abs(XMAT(i,K)) %
equality check
                   IKOUNT(j)=0;
                end

         for j=1:n
            if IKOUNT(j)==1
               IXFLAG(K)=1;
               break;
            else
               IXFLAG(K)=0;
            end

     NUMBER=0;
     for i=1:NTERM
         if IXFLAG(i)==1
            NUMBER=NUMBER+1;
            BETF(i)=BETAF(KID,NUMBER);
         else
            BETF(i)=0;
         end
     end

     NumTermLeft=n;

%===========================================================================
function PrintModel(file1,BETA,NumVar,VariableOrder,ModelType)

% Calculate Accuracy Error at Check Set Points
    fprintf('f=') ;
    fprintf(file1,'f=') ;

    % linear response surface model
    %fvalue=BETA(1);
    fprintf('%f',BETA(1)) ;
    fprintf(file1,'%f',BETA(1)) ;

    NUM=1;
    for i=1:NumVar
       NUM=NUM+1;
       %fvalue=fvalue+BETA(NUM)*X(i);
```

```
        if BETA(NUM)>0
            fprintf('+%f*x(%i)',BETA(NUM),i) ;
        else
            fprintf('%f*x(%i)',BETA(NUM),i) ;
        end

        if BETA(NUM)>0
            fprintf(file1,'+%f*x(%i)',BETA(NUM),i) ;
        else
            fprintf(file1,'%f*x(%i)',BETA(NUM),i) ;
        end
    end

    % quadratic response surface model

        for i=1:NumVar
            if VariableOrder(i)>=2
                 for j=i:NumVar
                     if VariableOrder(j)>=2
                         NUM=NUM+1;
                         %fvalue=fvalue+BETA(NUM)*X(i)*X(j);
                         if BETA(NUM)>0
                             fprintf('+%f*x(%i)*x(%i)',BETA(NUM),i,j) ;
                         else
                             fprintf('%f*x(%i)*x(%i)',BETA(NUM),i,j) ;
                         end

                         if BETA(NUM)>0
                             fprintf(file1,'+%f*x(%i)*x(%i)',BETA(NUM),i,j)
;
                         else
                             fprintf(file1,'%f*x(%i)*x(%i)',BETA(NUM),i,j) ;
                         end
    % cubic response surface model

        for i=1:NumVar
            if VariableOrder(i)>=3
                for j=i:NumVar
                    if VariableOrder(j)>=3
                        for k=j:NumVar
                            if VariableOrder(k)>=3
                                NUM=NUM+1;
                                %fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k);
                                if BETA(NUM)>0

fprintf('+%f*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k) ;
                                else

fprintf('%f*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k) ;
                                end

                                if BETA(NUM)>0

fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k) ;
                                else

fprintf(file1,'%f*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k) ;
                                end

    % 4 th order response surface model
```

```
        for i=1:NumVar
            if VariableOrder(i)>=4
                for j=i:NumVar
                    if VariableOrder(j)>=4
                        for k=j:NumVar
                            if VariableOrder(k)>=4
                                 for l=k:NumVar
                                      if VariableOrder(l)>=4
                                           NUM=NUM+1;

%fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l);
                                           if BETA(NUM)>0

fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l) ;
                                           else

fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l) ;
                                           end

                                           if BETA(NUM)>0

fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l) ;
                                           else

fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l) ;
                                           end

    % 5 th order response surface model

        for i=1:NumVar
            if VariableOrder(i)>=5
                  for j=i:NumVar
                      if VariableOrder(j)>=5
                          for k=j:NumVar
                             if VariableOrder(k)>=5
                                  for l=k:NumVar
                                      if VariableOrder(l)>=5
                                          for m=l:NumVar
                                               if VariableOrder(m)>=5
                                                   NUM=NUM+1;

%fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l)*X(m);
                                                   if BETA(NUM)>0

fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m) ;
                                                   else

fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m) ;
                                                   end

                                                   if BETA(NUM)>0

fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m) ;
                                                   else

fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m) ;
                                                   end

    % 6 th order response surface model
```

```
    for i=1:NumVar
       if VariableOrder(i)>=6
           for j=i:NumVar
              if VariableOrder(j)>=6
                  for k=j:NumVar
                      if VariableOrder(k)>=6
                          for l=k:NumVar
                              if VariableOrder(l)>=6
                                  for m=l:NumVar
                                      if VariableOrder(m)>=6
                                          for n=m:NumVar
                                              if VariableOrder(n)>=6
                                                  NUM=NUM+1;

%fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l)*X(m)*X(n);
                                                  if BETA(NUM)>0

fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m,n) ;
                                                  else

fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m,n) ;
                                                  end

                                                  if BETA(NUM)>0

fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m
,n) ;
                                                  else

fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m,
n) ;
                                                  end

    % 7 th order response surface model

        for i=1:NumVar
           if VariableOrder(i)>=7
              for j=i:NumVar
                  if VariableOrder(j)>=7
                     for k=j:NumVar
                         if VariableOrder(k)>=7
                             for l=k:NumVar
                                if VariableOrder(l)>=7
                                    for m=l:NumVar
                                        if VariableOrder(m)>=7
                                               for n=m:NumVar
                                                  if VariableOrder(n)>=7
                                                      for o=n:NumVar
                                                          if
VariableOrder(o)>=7
                                                              NUM=NUM+1;

%fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)*X(l)...

%*X(m)*X(n)*X(o);
                                                              if
BETA(NUM)>0

fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m
,n,o) ;
```

```
                                                               else
fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,k,l,m,
n,o) ;
                                                               end

                                                               if
BETA(NUM)>0
fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j
,k,l,m,n,o) ;
                                                               else
fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,
k,l,m,n,o) ;
                                                               end

    % 8 th order response surface model

    for i=1:NumVar
       if VariableOrder(i)>=8
           for j=i:NumVar
               if VariableOrder(j)>=8
                  for k=j:NumVar
                     if VariableOrder(k)>=8
                         for l=k:NumVar
                             if VariableOrder(l)>=8
                                 for m=l:NumVar
                                    if VariableOrder(m)>=8
                                       for n=m:NumVar
                                           if VariableOrder(n)>=8
                                              for o=n:NumVar
                                                 if VariableOrder(o)>=8
                                                     for p=o:NumVar
                                                         if
VariableOrder(p)>=8
                                                              NUM=NUM+1;
fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)...
*X(l)*X(m)*X(n)*X(o)*X(p);
                                                              if BETA(NUM)>0
fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j
,k,l,m,n,o,p) ;
                                                              else
fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM),i,j,
k,l,m,n,o,p) ;
                                                              end

                                                              if BETA(NUM)>0
fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NU
M),i,j,k,l,m,n,o,p) ;
                                                              else
fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM
),i,j,k,l,m,n,o,p) ;
                                                              end
```

```
    % 9 th order response surface model

     for i=1:NumVar
        if VariableOrder(i)>=9
            for j=i:NumVar
                if VariableOrder(j)>=9
                   for k=j:NumVar
                       if VariableOrder(k)>=9
                          for l=k:NumVar
                              if VariableOrder(l)>=9
                                  for m=l:NumVar
                                      if VariableOrder(m)>=9
                                         for n=m:NumVar
                                             if VariableOrder(n)>=9
                                                for o=n:NumVar
                                                    if VariableOrder(o)>=9
                                                       for p=o:NumVar
                                                           if
VariableOrder(p)>=9
                                                              for
q=p:NumVar
                                                                 if
VariableOrder(q)>=9
NUM=NUM+1;
%fvalue=fvalue+BETA(NUM)*X(i)*X(j)*X(k)...
%*X(l)*X(m)*X(n)*X(o)*X(p)*X(q);
                                                                    if
BETA(NUM)>0
fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NU
M),i,j,k,l,m,n,o,p,q) ;
                                                                    else
fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BETA(NUM
),i,j,k,l,m,n,o,p,q) ;
                                                                    end

                                                                    if
BETA(NUM)>0
fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',B
ETA(NUM),i,j,k,l,m,n,o,p,q) ;
                                                                    else
fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BE
TA(NUM),i,j,k,l,m,n,o,p,q) ;
                                                                    end

    % 10 th order response surface model

 for i=1:NumVar
    if VariableOrder(i)>=10
        for j=i:NumVar
           if VariableOrder(j)>=10
               for k=j:NumVar
                   if VariableOrder(k)>=10
```

```
                        for l=k:NumVar
                            if VariableOrder(l)>=10
                                for m=l:NumVar
                                   if VariableOrder(m)>=10
                                        for n=m:NumVar
                                            if VariableOrder(n)>=10
                                               for o=n:NumVar
                                                  if VariableOrder(o)>=10
                                                      for p=o:NumVar
                                                         if
VariableOrder(p)>=10
                                                            for q=p:NumVar
                                                                if
VariableOrder(q)>=10
                                                                    for
r=q:NumVar
                                                                        if
VariableOrder(r)>=10
                                                          NUM=NUM+1;

%fvalue=fvalue+BETA(NUM)*X(i)*X(j)...

%*X(k)*X(l)*X(m)*X(n)*X(o)*X(p)...
                                                          %*X(q)*X(r);
                                                          if BETA(NUM)>0

fprintf('+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',B
ETA(NUM),i,j,k,l,m,n,o,p,q,r) ;
                                                          else

fprintf('%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)',BE
TA(NUM),i,j,k,l,m,n,o,p,q,r) ;
                                                          end

                                                          if BETA(NUM)>0

fprintf(file1,'+%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(
%i)',BETA(NUM),i,j,k,l,m,n,o,p,q,r) ;
                                                          else

fprintf(file1,'%f*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%i)*x(%
i)',BETA(NUM),i,j,k,l,m,n,o,p,q,r) ;
                                                          end

fprintf('\n') ;
fprintf('\n') ;
```

Thesis_consopt;

```
function thesis_consopt
x0(1)=10
x0(2)=3
x0(3)=300
x0(4)=400
x0(5)=500
x0(6)=1
x0(7)=60
 [x,fopt]=fminunc(@battery_obj,x0);
 x
```

```
 fopt
```

Thesis_opt;

```
function thesis_opt
x0(1)=10
x0(2)=3
x0(3)=300
x0(4)=400
x0(5)=500
x0(6)=1
x0(7)=60
 [x,fopt]=fminunc(@battery_obj,x0);
 x
 fopt
```

Thesis_consopt;

```
function thesis_consopt
numvar=7 ;  %  Number of variables (degisken sayisi)
% OptimizationMethod=1 for Local Optimization Method
% OptimizationMethod=2 for Genetic Algorithm Optimization Method
OptimizationMethod=1;
x0(1)=1
x0(2)=6
x0(3)=300
x0(4)=400
x0(5)=500
x0(6)=7
x0(7)=60

xl(1)=1
xl(2)=1
xl(3)=150
xl(4)=250
xl(5)=250
xl(6)=1
xl(7)=10

xu(1)=10
xu(2)=6
xu(3)=300
xu(4)=400
xu(5)=500
xu(6)=7
xu(7)=60
if OptimizationMethod == 1
    options=optimset('LargeScale','off','MaxFunEvals',100000) ;

[x,FunVal,ExitFlag,Output]=fmincon(@battery_obj,x0,[],[],[],[],xl,xu,@batte
ry_con,options)  ;
else
    % setting the genetic algorithm parameters
    options=gaoptimset('PopulationSize', 1000,'Generations',
50000,'PlotFcns',{@gaplotbestf,@gaplotmaxconstr,@gaplotbestindiv},'Display'
,'iter');

[x,FunVal,ExitFlag,Output]=ga(@battery_obj,numvar,[],[],[],[],xl,xu,@batter
y_con,options)  ;
end
```

```
% Optimum degerler
fprintf('OPTIMUM DEGERLER: \n') ;
x
FunVal
```