MARMARA UNIVERSITY
FACULTY OF ENGINEERING

DESIGN AND SIMULATION OF COOLING SYSTEM OF LITHIUM-ION BATTERIES ON ELECTRICAL VEHICLES

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DESIGN AND SIMULATION OF COOLING SYSTEM OF LITHIUM-ION BATTERIES ON ELECTRICAL VEHICLES

by SETTAR SAĞLAM, OĞUZHAN ÖZ

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OĞUZHAN ÖZ and SETTAR SAĞLAM

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ABSTRACT

DESIGN AND SIMULATION OF COOLING SYSTEM OF LITHIUM-ION BATTERIES ON ELECTRICAL VEHICLES

In recent years interest in electrical vehicles increased because of global warming, depletion of fossil fuel reserves and greenhouse gas emission into the atmosphere. Electrical vehicles have increased in the automotive industry because these vehicles reduce carbon emissions and have high efficiency.

The increase of using electric vehicles has led to new problems. The biggest problem in electrical vehicles is range. To increase the range in electrical vehicles cooling the battery is one of the important parts. To optimize the life of battery we should find the best cooling system for the batteries this will improve the range of electrical vehicles.

There are a lot of heat management system in batteries. We could use air, liquid and phase change material for cooling the battery. Thermal, physical, chemical and economical properties are important for choosing the best cooling system.

In this project we worked on direct liquid cooling system. We are going to simulate the thermal effect of cooling system in Ansys analyzing program. We will try to do this simulation as efficient as we can and we will simulate the time dependent heat flux in the program.

We worked in this project compare and simulate differences between different form like cylindrical and rectangular also we will compare the different application of tube’s shape.

SYMBOLS

i: Current density (A/m^2)

Q: Heat generation rate (W/m^3)

E: Energy

V: Volume (m^3)

$\boldsymbol{q}''$**:** Heat flux (W/m^2)

k: Heat conduction coefficient (W/m °C)

h: Heat transfer coefficient (W/m^2 °C)

m: mass (kg)

c: Concentration of lithium (mol/m^3)

cp: Specific heat at constant pressure (J/kg °C)

T: Temperature (°C or K)

$\boldsymbol{\sigma}$**:** Stefan-Boltzmann coefficient (W/$m^2(K)^4$

ρ: Density (kg/m^3)

A: Surface Area (m^2)

t: Time (s)

ABBREVIATIONS

ICE: Internal Combustion Engine

EV: Electric Vehicles

R&D: Research and Development

DC: Direct current

ECU: Electronic control unit

Wh/kg: Specific energy

Wh/m^3: Energy Density

PCM: Phase change material

kW: Power

CFD: Computational fluid dynamics

Km/h: Speed

HEV: Hybrid electric vehicles

NASA: National Aeronautics and Space Administration

FEM: Finite element analysis

LiFePO4: Lithium iron phosphate

LiCoO2: Lithium cobalt oxide

Li-ion: Lithium-ion

NiCd: Nickel cadmium

NCA: Nickel cobalt aluminum oxide

NiMH: Nickel metal hydride

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1.INTRODUCTION

The main factor that started the automobile age is the steam age. The first steam car was produced in France in 1769 for the purpose of carrying cargo for the French army [1]. When these machines which take their energy from steam, became insufficient for transportation so todays known vehicles began to born. In 1881, the ‘’La Rapide’’ model for six people and reaching a speed of 63 km/h was launched [2]. Later models similar to it were produced, but internal combustion engines and petrol began to gain acceptance in the market. Many prototypes were made, but the real automotive was produced in 1860 with the discovery of internal combustion engine.

1.1 Internal Combustion Engine Vehicles

ICE is one of the most important inventions on earth. It is the most popular power plant today with its different designs that have been used for 150 years. It used petrol/diesel as a fuel, and this gives very important chance against other vehicles such as hybrid and electrical vehicles. This can be explained by the energy of petrol/diesel fuel compared to other power sources. In fact, its basic principle is to convert chemical energy to mechanical energy. Engineers are still working to improve it and increase its efficiency [3].

Figure 1.1. Internal Combustion Engine

1.2 Hybrid Vehicles

In other words, hybrid means mixed. In terms of automotive, it is used to express the use of two different power sources together. These hybrid vehicles have both electric and gasoline engines, and these cars are self-charging models. Hybrid vehicles can move by using only the power of the electric motor or by using gasoline and electric motors together in different situations. This system provides maximum efficiency and decides automatically which system will be used in current situation. Hybrid vehicles provide quiet and comfortable driving with very low fuel consumption, it also pollutes the environment less. These hybrid cars are self-charging cars.

There are three types of hybrid vehicles such as a full hybrid (FHEV), mild hybrid and plug-in hybrid (PHEV). A full hybrid vehicle can run with internal combustion engine and electric engine together. These types of vehicles cannot be charge from outside charger only combustion engine can charge the battery. Plug-in hybrid vehicles use higher capacity hybrid battery and can be charged from the electricity grid. A mild hybrid vehicle can run only internal combustion engine and electric engine together and they also called as parallel hybrid vehicles. Additional equipment such as the use of higher capacity, expensive hybrid batteries and external charging facilities negatively affect the cost of the vehicle. Because of that these vehicles do not submitted to some countries market [4].

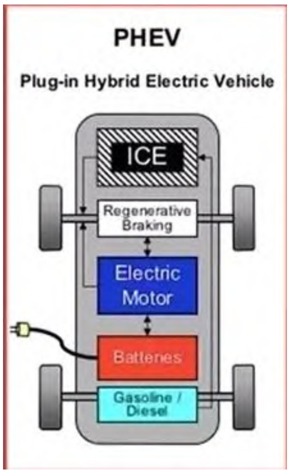
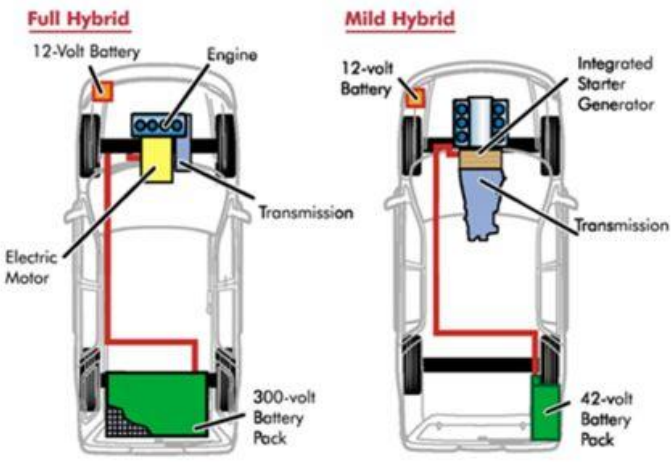


Figure 1.2. Hybrid Vehicle Types

1.3 Electric Vehicle

We know that all electrical vehicles run on electricity only. These electrical vehicles use electric motors powered by rechargeable battery packs. There are some advantages and disadvantages of using electrical vehicles. Some advantages are efficiency of energy, environmentally friendly and reduced energy dependence. If we compare it with internal combustion engine (ICE) problem of electrical vehicles are driving range. In this project we will try to optimize the battery by simulating the cooling system. To improve the longevity of batteries it is important to control the temperature. High and low temperatures are not wanted in these batteries [1].



These types of cars save fuel as well as reduce urban pollution and carbon emission. Because of that it is believed that they are cars of the future. The degree of reduction carbon dioxide emission depends on electricity generation and a 30% reduction is expected [5]. These electric vehicles need a charging station for collecting energy. Installing more charging stations will increase the use of these vehicles.

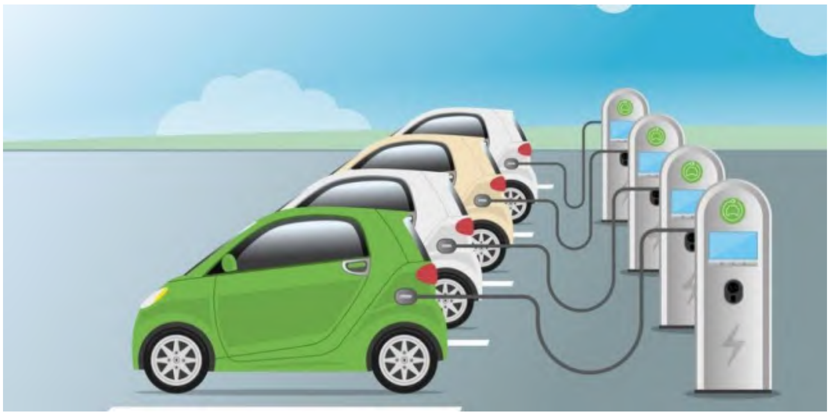


Figure 1.3. Electric Vehicles

1.3.1 History of Electrical Vehicles

Contrary to popular belief, the history of electrical vehicles, which have an agenda of the last 20-30 years, dates to the early 1800s. The first electrical vehicle known in history was invented by Thomas Davenport in America and its type was the locomotive. Electric vehicles produced in other countries during the same period did not have the ability to be charged. The use of electric vehicles expanded and in 1897 they were used as taxis in New York. In the same year, the first large-scale American electric car company was established. Of the 4192 vehicles produced in the United States in 1900, %28 was electrified, representing approximately one-third of the market.

Vibration, noise, and sound problems occurring in gasoline-powered vehicles produced in this period had an important place in the preference of electrical vehicles.

The gasoline-powered vehicle produced by Ford in 1908 completely changed the market. In 1912, electric vehicles were almost replaced by these gasoline-powered vehicles. The most important reason for this is that an electric vehicle produced in the same period was 1750 dollars, while a gasoline powered vehicle was 650 dollars. In the 1920's, electrical vehicles are not preferred anymore. The main reason this was the lack of horsepower and range problems.

In the 1960's increasing of the air pollution and harmful fuels brought the electrical vehicles back to the agenda. BMW designed a different model in 1972 and presented it at the

Olympics, but never put it into mass production. The OPEC oil crisis in 1973 accelerated the studies of electric vehicles. In 1976, America organized state-funded incentive programs for hybrid and electric vehicles. Although General Motors CEO Roger Smith produced the EV1 Model, which it's called ''the most efficient vehicle in the world'', this model took its place in history only to be preserved in museums in 1996.Toyota had very important studies on hybrid and electric vehicles between 1996-2006 years. It was preferred to use vehicles produced by major automobile manufacturers such as Honda, Ford and Nissan for leasing rather than sales. In 2006, Tesla production appeared as a revolutionary step in electric vehicles. Unlike other vehicles, Tesla is designed to travel 200 km on a single charge. The model that Tesla launched in 2011 under the name Roadcaster had a range of 240km.In 2010, the Nissan Leaf, which sold more than 250000 units in 6 years with its price and performance, was launched for the first time [11]. More than twice the previous year, 113.000 electric vehicles were sold in the world in 2012, mainly in the USA, Japan and China, and it is expected that 20 million electric vehicles will be on the road by 2021. With government incentives, R&D in electric vehicle Technologies, a significant increase in infrastructure and decrease in battery costs, the place of these vehicles in the market is expected to become even more effective in the near future.

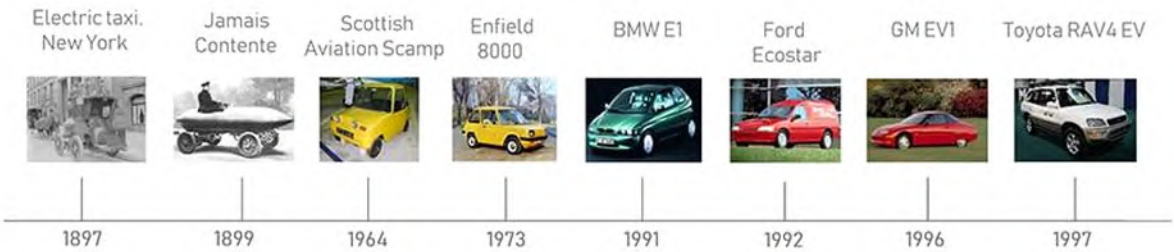


Figure 1.4. History of Electric Vehicle 1897-1997

1.4 Battery Technology of Electric Vehicle

Electric vehicle battery used to power the electric motors of the vehicle. These batteries are mostly rechargeable batteries and most common battery type is lithium-ion batteries. These batteries are specifically designed for a high kw-h capacity. Other types of rechargeable batteries used in electric vehicles include lead-acid, nickel-cadmium, nickel-metal hybrid, zinc-air, sodium nickel chloride batteries [6].

Battery Types	Nominal Voltage (V)	Density of Energy (Wh/kg)	Cycle Life	Operating Temperature(°C)
Li-ion	36	$118-250$	2000	$-20,+60$
Pb-acid	2	35	1000	$-15,+50$
Zebra	2.6	$90-120$	>1200	$+245,+350$
NiCd	1.2	$50-80$	2000	$-20,+50$
NiMH	1.2	$70-95$	<3000	$-20,+60$
$\text{LiFeP}O_4$	3.2	120	>2000	$-45,+70$
LiPo	3.7	$130-225$	>1200	$-20,+60$
Zn-air	1.65	460	200	$-10,+55$
Li-S	2.5	$350-650$	300	$-60,+60$
Li-air	2.9	$1300-2000$	100	$-10,+70$

Table 1.1. Battery Types and Specifications

Batteries for electric vehicles are characterized by their high power-weight ratio, specific energy and energy density. Smaller and lighter batteries are desirable because they reduce the weight of the vehicle and improve its performance.

The battery pack has a large part in cost of electric vehicle. As of 2019, the cost of electric-vehicle batteries has fallen 87% since 2010 on a per kilowatt-hour basis [7]. According to study of the United States National Research Council the cost of lithium-ion battery pack was about US$1,700/kWh [8]. In February 2016 battery prices fell 65% since 2010 and reaches US$350/kWh [9]. These studies concludes that battery prices will continue to fall.

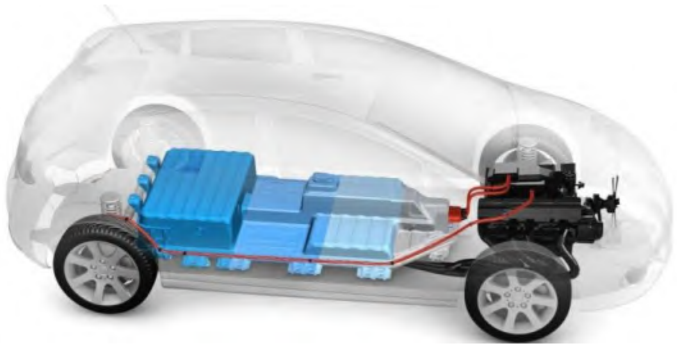


Figure 1.5. Electric Vehicle Battery

Battery packs includes battery modules which has many hundreds of small battery cells arranged in series or parallel configuration to required voltage and current capacity. For example, as in Tesla Model 3 to supply 400V nominal pack will often have around 96 series blocks. In hybrid and plug-in hybrid vehicles have nominal pack voltages between 400V to 800V and higher for electric vehicles. Electric vehicles need higher voltages to allow more power to be transferred with less loss over the same diameter of copper cable.

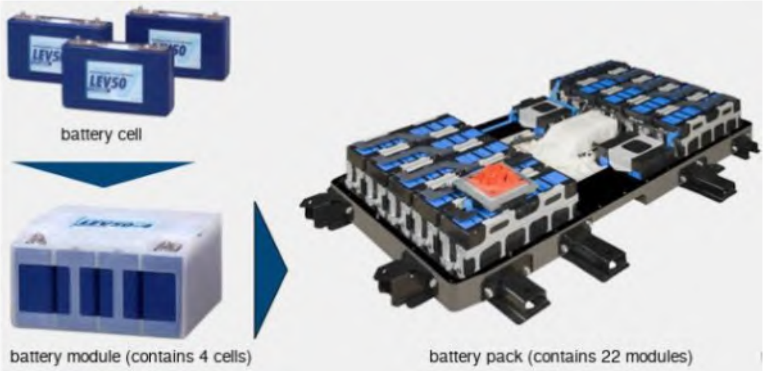


Figure 1.6. Battery pack (modules and cells) of Mitsubishi

1.4.1Lithium-Ion Batteries

Li-ion battery type is the most common rechargeable battery type used in electric vehicles and other electronic devices. A prototype Li-ion battery was developed by Akira Yoshino in 1985, and then a commercial Li-ion battery was developed by a Sony and Asahi Kasei team led by Yoshio Nishi in 1991.

In the li-ion batteries lithium ions move from negative electrode through an electrolyte to the positive electrode during discharge, and back when charging. As a positive electrode lithium compound is used and as a negative electrode graphite compound is used. Li-ion batteries have a high energy density and low self-discharge. Specific energy density of li-ion batteries is 100 to 250 W*h/kg, volumetric energy density 250 to 580 W*h/L, specific power density 300 to 1500 W/kg [10]. Research and developments are ongoing to reduce the Li-ion batteries high cost, extend its lifetime and address safety concerns regarding overheating.

The positive electrode reaction is:

$$\mathbf{Li}\boldsymbol{C_0O_2} \Leftrightarrow \boldsymbol{Li_{1-x}C_0O_2} + \mathbf{x}\boldsymbol{Li^+} + \mathbf{x}\boldsymbol{e^-}$$

The negative electrode reaction is:

$$\boldsymbol{xLi^+ + xe^- + xC_6} \Leftrightarrow \mathbf{xLi}\boldsymbol{C_6}$$

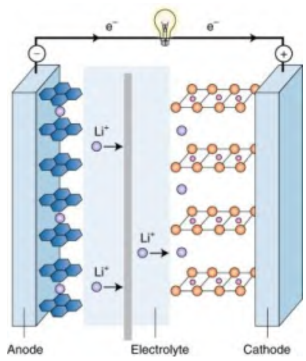


Figure 1.7. Li-ion battery

Lithium-ion batteries reaches maximum power when temperature varies between 20° C to 40° C.

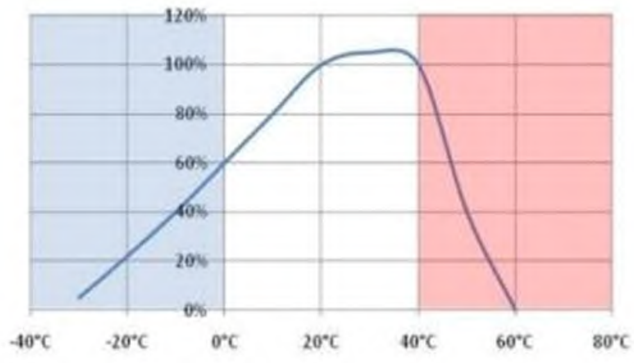


Figure 1.8. Battery power versus temperature graph (Matthe, et al., 2011)

1.4.2 Battery Pack Placement

In electric vehicles location of battery pack is very important. Battery pack should be placed in a space which is otherwise unused. For choosing the place, center of gravity should be low and mechanical stress and fatigue should be minimized. In location of the battery pack there should be air circulation to maximize the thermal efficiency of battery. Also, battery pack should be located in outside of passenger areas because of safety reasons such as high voltage. Researchers said that best location for battery packs is center of the vehicle, but it should have ground clearance which requires supporting structure designs because of potential threat of impact [19]. Also, main reason of this selection is rear and front end of the vehicles has high probability of collision. Table 1.2. shows us the battery pack placement for different automobile manufacturers.

Vehicle	Battery Type	Battery Size (kwH)	Electric Range(km)	Battery Location
BMW i3	Lithium – ion	18.8	130 – 160	Centre
Tesla Model S	Lithium – ion	60 85	335 426	Centre
Chevrolet Spark	Lithium – ion	21.3	132	Rear

Mitsubishi 1 MiEV	Lithium – ion	16	100	Centre
Toyota RAV4	Lithium – ion	35	166	Centre
Ford Focus	Lithium – ion	23	122	Centre
Nissan Leaf	Lithium – ion	24	200	Centre
Volkswagen e-Golf	Lithium – ion	24.2	190	Centre
Fiat 500e	Lithium – ion	24	140	Rear
BYD e6	Lithium – ion	61.4	300	Centre
Bollore Bluecar	Li-ion Polymer	30	250(City) 150(Highway)	Centre

Table 1.2: Battery pack and its location

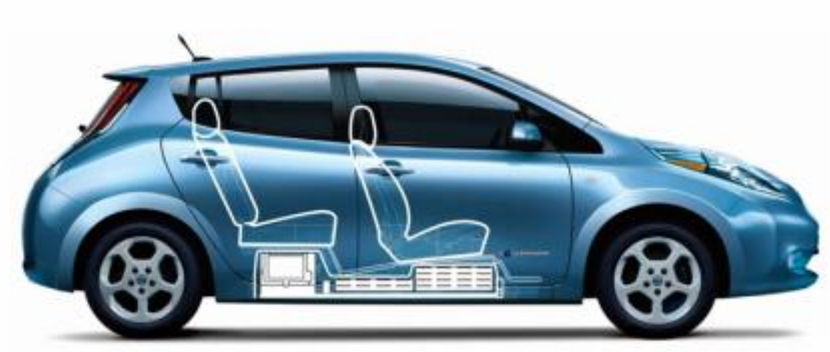


Figure 1.9. Battery pack location of Nissan Leaf

1.4.3 Battery Management Systems (BMS)

Battery management system (BMS) are systems that control and manage battery packs consisting of one or more cells during the charge and discharging. They are the structures that interfere with the system when the optimum values are exceeded by measuring the important values such as current, voltage and temperatures. The system formed by the combination of more than one cell is called battery and battery packs. Battery packs consist of cells connected in series or parallel. In battery packs, serial connections determine the voltage, parallel connections determine the current and capacity that can be drawn. BMS's are used to ensure coordination between these series and parallel connected systems. BMS's are electronic systems that control the rechargeable batteries. The main functions of BMS' systems consist of data monitoring, calculation, protection and most importantly optimization [13]. The most important things for the BMS are battery state of charge (SOC) and state of health (SOH). The ratio of the amount of the charge available in the battery to the total capacity of the battery is called SOC. The ratio of the total available capacity of the battery to the capacity of battery before its used for example as soon as it is manufactured, is called SOH. For the charger to safely charge the battery and manage the charging process efficiently, it must interact with the BMS [14].

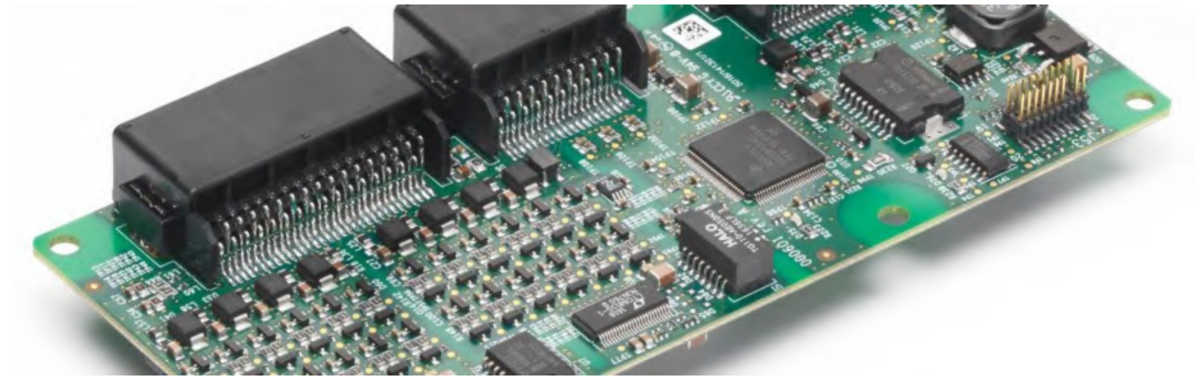


Figure 1.10. Li-ion battery management systems

1.4.4 Battery Thermal Management Systems (BTMS)

To provide safety and performance to the battery thermal properties of the battery should be controlled by thermal management systems. BTMS has four main functions to provide best positions for the battery: cooling, heating, insulation, ventilation.

Battery cells produces heat besides electricity. This heat is undesirable factor for the battery because high temperatures are not wanted for the maximum power and cooling systems is required for the BTMS. In cold climates battery temperature falls below the optimum temperature to increase the temperature of the battery heating systems is required in BTMS. In some conditions temperature difference can be larger between the inside and outside of the battery pack than in normal conditions and this situation requires insulation for the BTMS. There are some dangerous gases in the battery packs so these gases should be removed from the system and these requires ventilation systems in BTMS.

1.4.4.1 Air Cooling and Heating

Systems that use air to cool or heat the battery are called air-cooled systems. Inlet air can be taken directly from the atmosphere and from the cabin or condenser and evaporator of the air conditioning system. These systems are divided into passive and active systems. Both types of systems have cooling and heating power. In both systems, air is entered the system with the help of a fan, so the amount of energy required varies according to the type of system. In addition, in these systems, a heat exchanger can be used after the battery pack to increase the system efficiency by providing heat recovery from the hot air coming out of the coil [16]. In figure 1.11. and 1.12. you can see the mechanism of forced air systems.

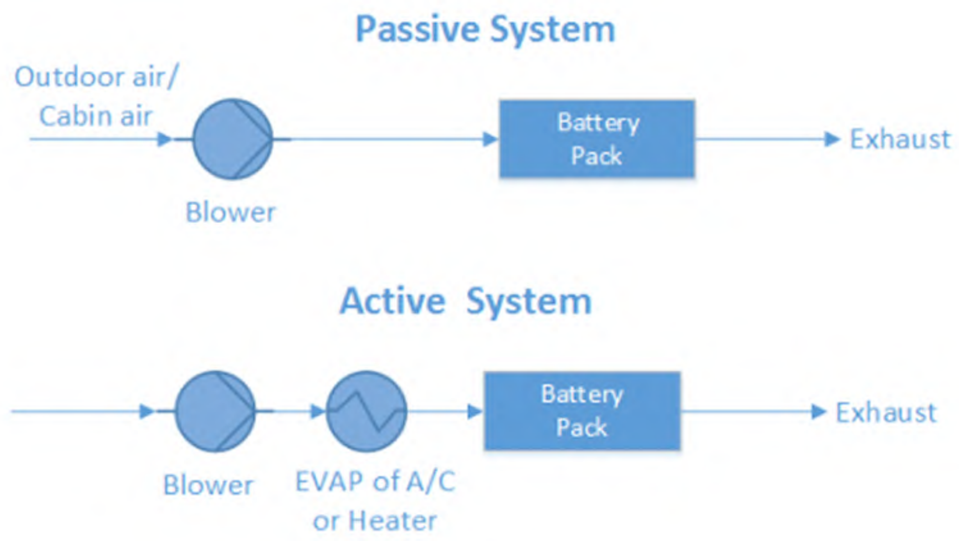


Figure 1.11. Forced air systems (passive and active)

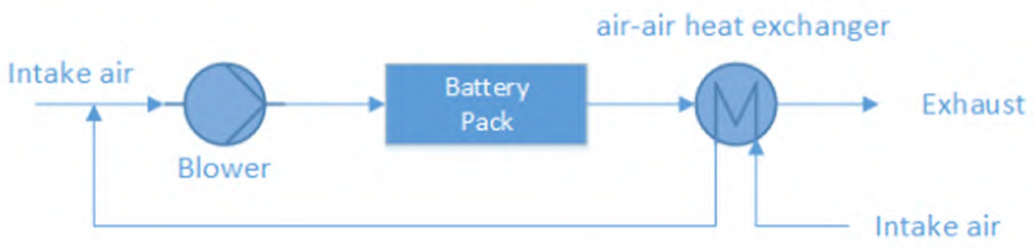


Figure 1.12. Forced air systems with heat recovery.

1.4.4.2 Liquid Cooling and Heating

Liquids can consider as heat transfer fluid to transfer heat. There are two types of liquids in thermal management systems. First one is dielectric liquid which is directly contacts with the battery cells, for example mineral oil. Second one is conducting liquid which has indirect contact with the battery cells, for example mixture of ethylene glycol and water. To provide better isolation between the outside and battery module indirect contact systems are preferred. Indirect contact systems have better safety performance. We can divide liquid system into two other different parts such as passive or active systems. Passive liquid system for example heat-sink for cooling is radiator, these systems cannot heat. Liquid circulates by the pump in a closed system as you can see in the Figure 1.13 below. Heat transfer fluid circulates in the system and reduces the heat of the system. The cooling power depends on the temperature differences between outside and battery.

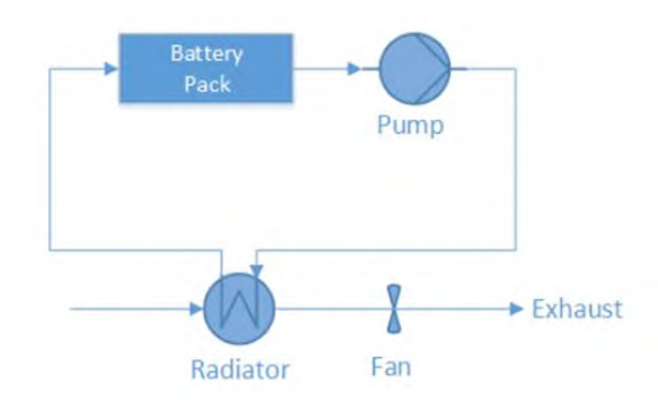


Figure 1.13. Passive Liquid Cooling System

In active liquid cooling system, there is another loop added to the similar system of the passive one and this loop is an air conditioning loop, so we have two different loops in the active liquid cooling system. Instead of the radiator evaporator used as heat exchanger for cooling and connect the loops as you can see in the Figure 1.14 below. During heat operation valve will be switched and the heat exchanger work as condenser and the lower heat exchanger works as an evaporator and this heating operation is the main difference between the passive and active liquid cooling system.[15]

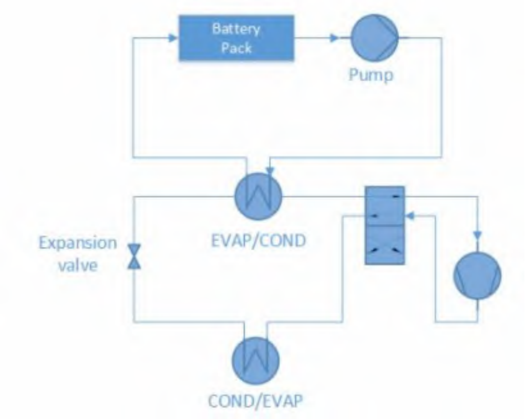


Figure 1.14. Active Liquid Cooling System

1.4.4.3 Phase Changing Material (PCM)

PCM absorbs heat and stores as latent heat until it reaches the maximum heating during melting. This system provides to the battery to keep the temperature in same level and delay the rise of the temperature. Because of that PCM is used as conductor in BTMS in battery cells. Air cooling or liquid cooling systems always used together with PCM to optimize the battery temperature [15].

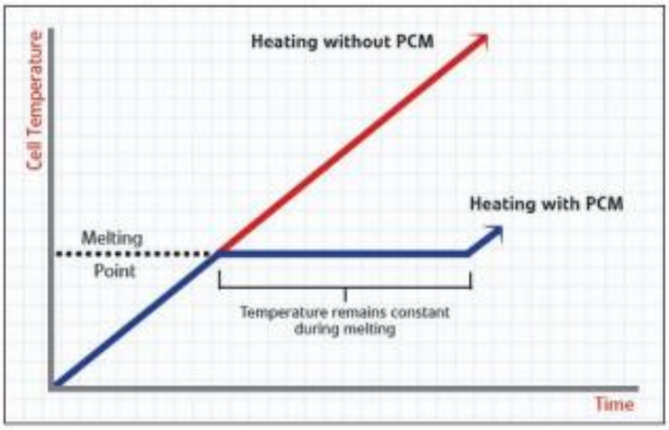


Figure 1.15. Cell Temperature versus time graph by using PCM (Charged,2014)

1.4.4.4 Heat Pipe

Heat pipes help high effective conductivity in electrical devices such as laptop. Heat pipes come in different types as flat, vibrating and tube types. Heat pipes work with phase change heat transfer. The system consists of a sealed container with a capillary material outside surface to convert the condensate into steam. Air or fluid thermal management systems cannot deliver the expected performance under intense conditions. Heat pipes and especially vibrating heat pipes are different alternatives. With this system, it was concluded that the surface of the heat pipe and batteries should be as close as possible to reduce the temperature significantly [17].

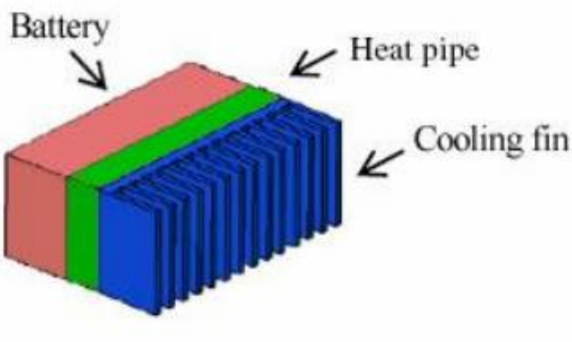


Figure 1.16. Heat Pipe Cooling System

1.4.4.5 Thermo-electric Module

This thermo-electric module is used to improve power of the passive air systems. Thermo-electric module can create temperature difference by using electric voltage. This means thermo-electric module consumes electric directly. There are two fans to improve the heat transfer as you can see in the figure 1.17 below. Using passive air-cooling system and thermo-electric module together will be able to cool the battery in a fast and efficient way. In this system by changing the poles of electrodes as reverse will be provide switch between the cooling and heating part [15].

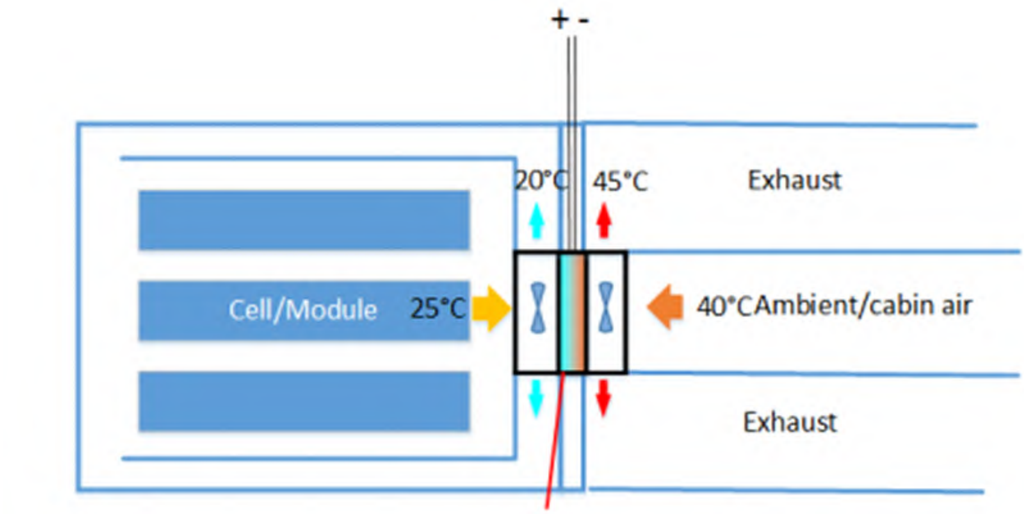


Figure 1.17. Thermo-electric cooling/heating system

1.4.4.6 PTC Heater

PTC Heaters have many different systems by using their own voltage-current or current-time characteristics. One of them operates as a self-regulating heater and a PTC heater can be hold in constant temperature through setting the resistance of the PTC heater automatically as you can see in the figure 1.18 below.

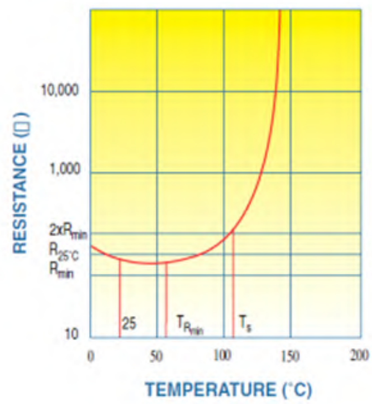


Figure 1.18. Resistance versus Temperature for a PTC Heater (Digikey,2014)

2. Introduction to Analysis

Until this section, we gave detailed information about electric vehicles and battery thermal management systems of electric vehicles. We used Ansys Fluent for calculations of thermal management of the battery and also, we did our analysis time dependent. In this thesis we used water-based cooling system. In this analysis we observed maximum temperature and pressure on the battery system. We did a lot of analysis for optimizing the thermal efficiency of cooling system.

Analyzes were carried out using the finite element method. Finite element method is a numerical method, especially in solid mechanics, fluid mechanics and heat transfer problems. It is very advanced technique used to solve problems such as vibration with the help of computers. In the finite elements method (FEM) models are divided into a number of elements. These elements are connected with each other at certain points, these points are called as nodes.

2.1. Module Properties and Geometry

In our battery module we used 16 rectangular battery cells different from most known cylindrical Li-ion batteries. Normally in a battery module there are hundreds of battery cells and in one package there could be battery cells more than 1000 but it is not correct to make analysis with a lot of battery cells, so we used 16 battery cells in our analysis. We used liquid cooling system in our analysis because it is more compact and efficient way of cooling battery. Our cooling liquid is water. In analysis we changed the velocity and pressure of water. The effect of these parameters on the thermal performance was investigated.

We designed the batteries in SolidWorks program. In design we were inspired by Daniel Grimmeisen's article [20]. Our first design with 5 straight cooling channel can be seen in figure 2.1. below and our curved cooling channel system design in figure 2.2. below.

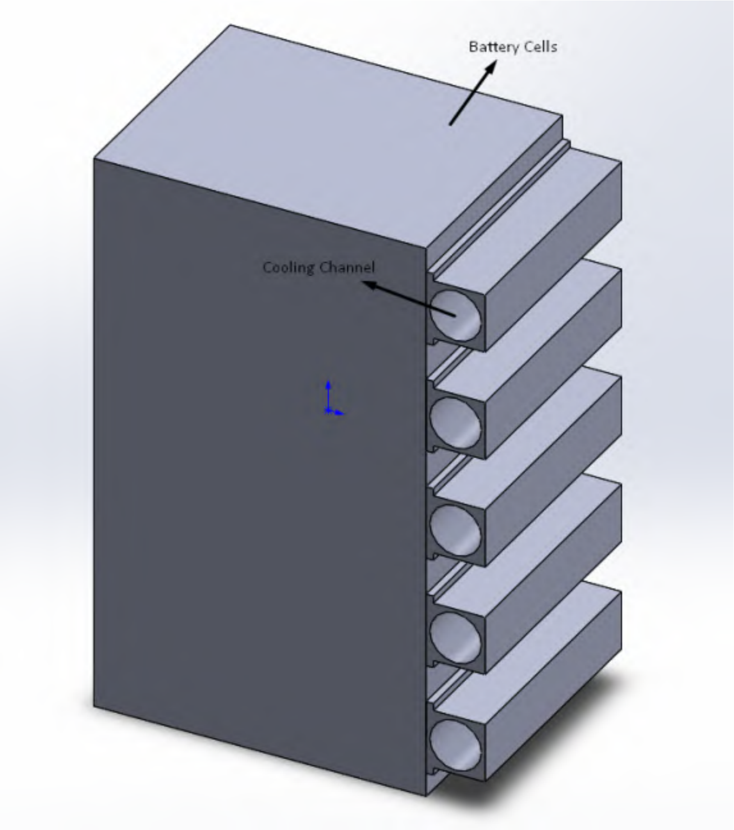


Figure 2.1. Design 1

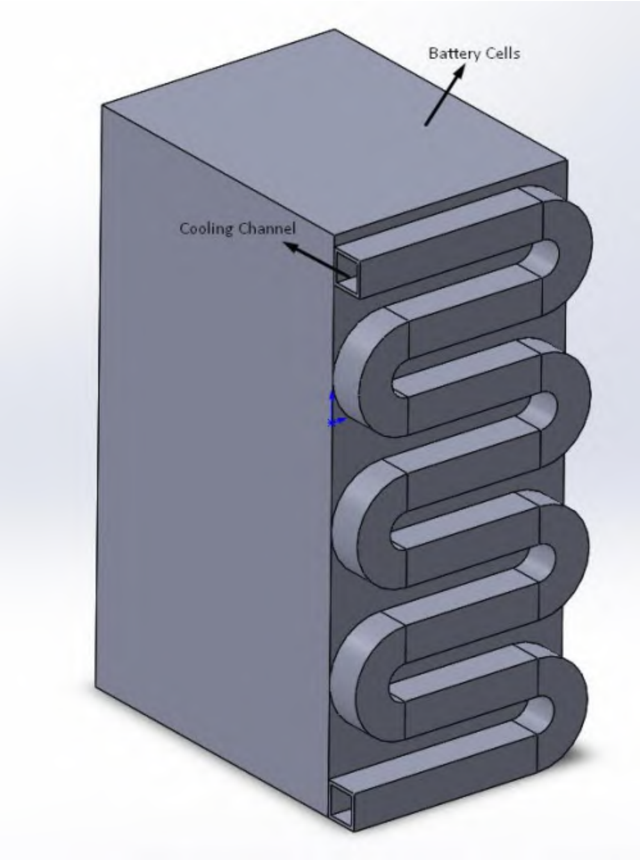


Figure 2.2. Design 2

Detailed information about battery cells is given in table below.

Size	153 mm x 90 mm x 4.375 mm
Cell Capacity	10.03 Ah
Energy Content	36.7 Wh
Cell Voltage	3.66 V

Table 2.1. Specification of the battery cell.

In this battery module we did our calculations based on 1C discharge rate. Our heat generation rate is 85088 W/m^3 [21].

2.2 Heat Transfer

2.2.1 Heat Transfer Coefficient

Heat transfer coefficient is used for predicting the performance of the heat exchange. This coefficient expressed by following equation.

$$\mathbf{q} = \mathbf{UA}\Delta \boldsymbol{T_M} \tag{1.1}$$

q = Heat Transfer rate [W]

U= Overall heat transfer coefficient [W/(m^2*K)]

A = Heat transfer surface area [m^2]

Tm = Approximate mean temperature different [K]

2.2.2 Heat Transfer with Heat Exchanger

For a controlled volume, the conservation of energy is stated in the expression as

$$\frac{d\boldsymbol{E_{st}}}{d\boldsymbol{t}} = \dot{\boldsymbol{E}}_{\boldsymbol{in}} - \dot{\boldsymbol{E}}_{\boldsymbol{out}} + \dot{\boldsymbol{E}}_{\boldsymbol{g}} \tag{1.2}$$

E_{st}= Stored thermal and Mechanical Energy

$\dot{E}_g$= Thermal Energy Generation Rate

$\dot{E}_{in} - \dot{E}_{out}$ = Thermal and Mechanical Energy Transport Rate

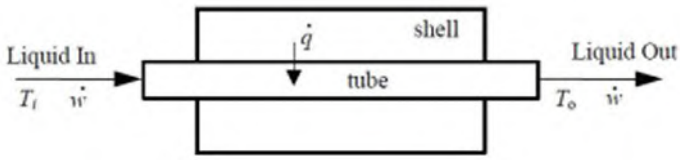


Figure 1.5 Tube and shell heat exchanger schematic

The equation 1.3 reduces to the following form of the steady-flow energy equation.

$$\mathbf{mCp}\ \frac{dT_0}{dt} = \dot{m}\mathbf{Cp}(T_i - T_0) + \dot{q} \qquad (1.3)$$

m = Fluid mass within the tube [kg]

$\dot{m}$ = Fluid mass flow rate through the heat exchanger [kg/s]

T_i , T_0 = Temperature of fluid entering and leaving tubes [°C]

Cp= Specific thermal capacity of fluid [J/(kg*K)]

$\dot{q}$ = Heat transfer rate to the liquid in the tube [W]

This equation can be used for heater, radiator, chiller.

2.3. Material Properties

Our Lithium-Ion battery cells properties is shown in table below.

	Cell(avg)	Separator	Cathode	Anode
Cp $[J * g^{-1} * K^{-1}]$	1.36	$1.93 - 2$	1.25	1.2
K $[W * m^{-1} * K^{-1}]$	0.4	$0.12 - 0.22$	0.4	1.4
ρ $[g * m^{-3}]$	$2.047 * 10^{\wedge}6$	$9.02 - 9.06 * 10^{\wedge}5$	2.208*10^6	$1.41 * 10^{\wedge}6$

Table 2.2. Lithium-Ion Battery Cells Properties

We used average cell values in our analysis. We used aluminum (Al 6061) as cooling channel material.

2.4. Boundary Conditions

The analyzes are time dependent and the discharge rate of the cells is taken into account. The analysis time was determined as 600 seconds. Initial water inlet temperature and initial battery cells temperature is 300 K in all analyzes. We changed inlet water velocity and pressure to observe the thermal management for different channel types. We determined water inlet velocities as 0.1 m/s, 0.3 m/s and 0.9 m/s and inlet pressures as 1 atm, 2 atm, 3 atm.

The methods of conduction and convection of heat transfer were analyzed. Natural convection and radiation are neglected in the system. In the analysis, electrochemical structure of the batteries was not examined.

In setup part of Ansys we used pressure-based type, absolute velocity formulation and transient time.In models we opened the energy and viscous-SST k-omega models. Our input for heat generation rate is 85088 W/m^3 in the boundary condition part for battery cells [21]. We used velocity-inlet in our first analysis and we changed the inlet water velocity for the second part we used pressure-inlet and we changed the inlet water pressure and for turbulence specification method we used intensity and viscosity ratio with 5% turbulent intensity and 10 turbulent viscosity ratio. As a method we used SIMPLEC and our skewness correction was zero. We made a hybrid initialization and we used fixed typed, user-specified method for calculation. We chose time step size as 1 second and 600 time steps because it is convenient for our mesh quality.

2.5. Mesh Structure of Battery Modules

Mesh structure is very important because the purpose of mesh is to break the model into physical parts it enables mathematical operation to be performed on it.

2.5.1 Mesh Structure of Design 1

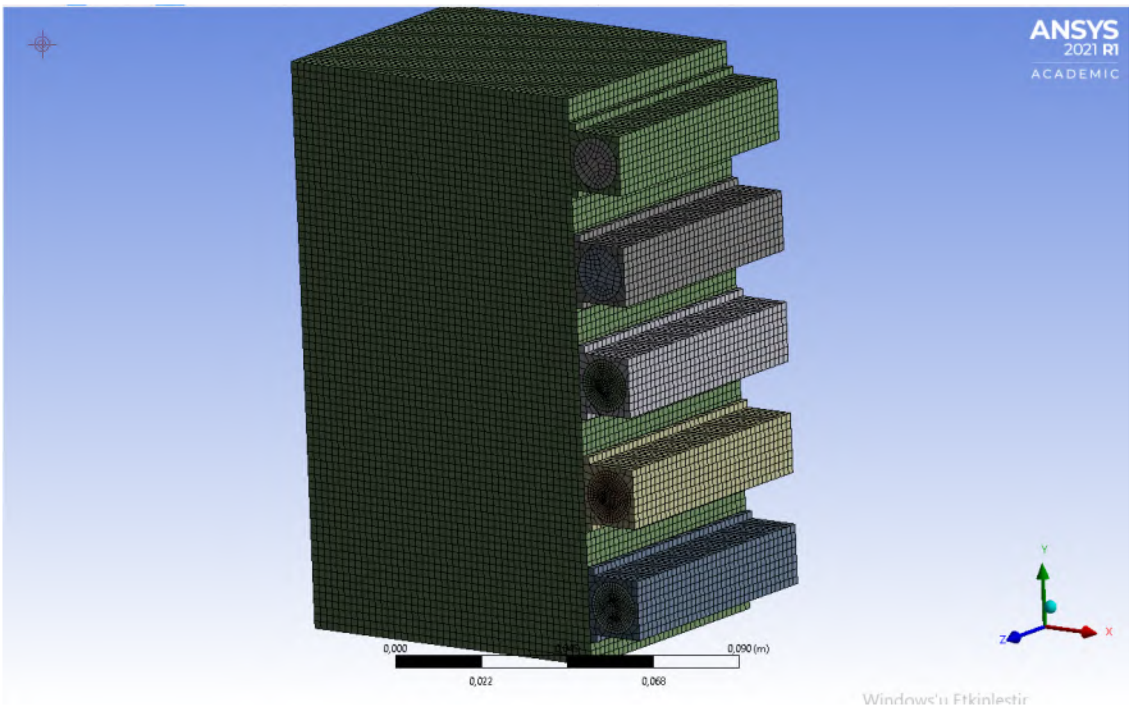
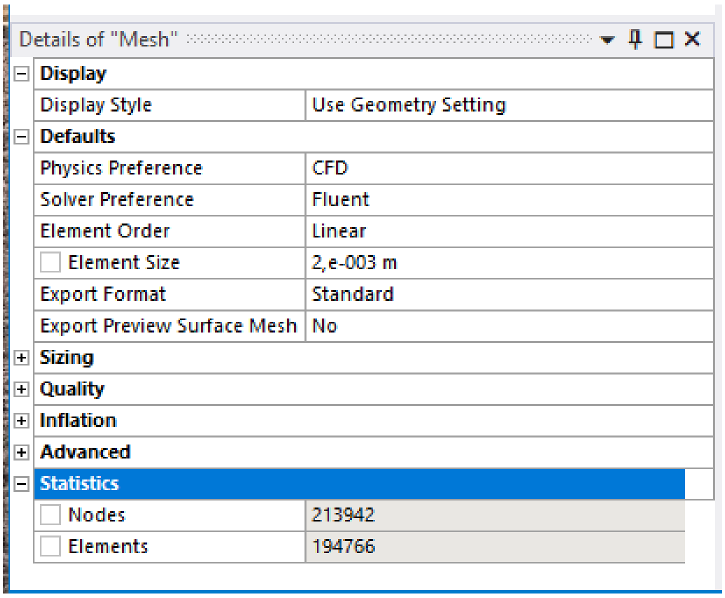


Figure 2.3. Mesh Structure of Design 1



Details of "Mesh"

Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	2,e-003 m
Export Format	Standard
Export Preview Surface Mesh	No
Sizing	
Quality	
Inflation	
Advanced	
Statistics	
Nodes	213942
Elements	194766

Figure 2.4. Details of Mesh for Design 1

2.5.2 Mesh Structure of Design 2

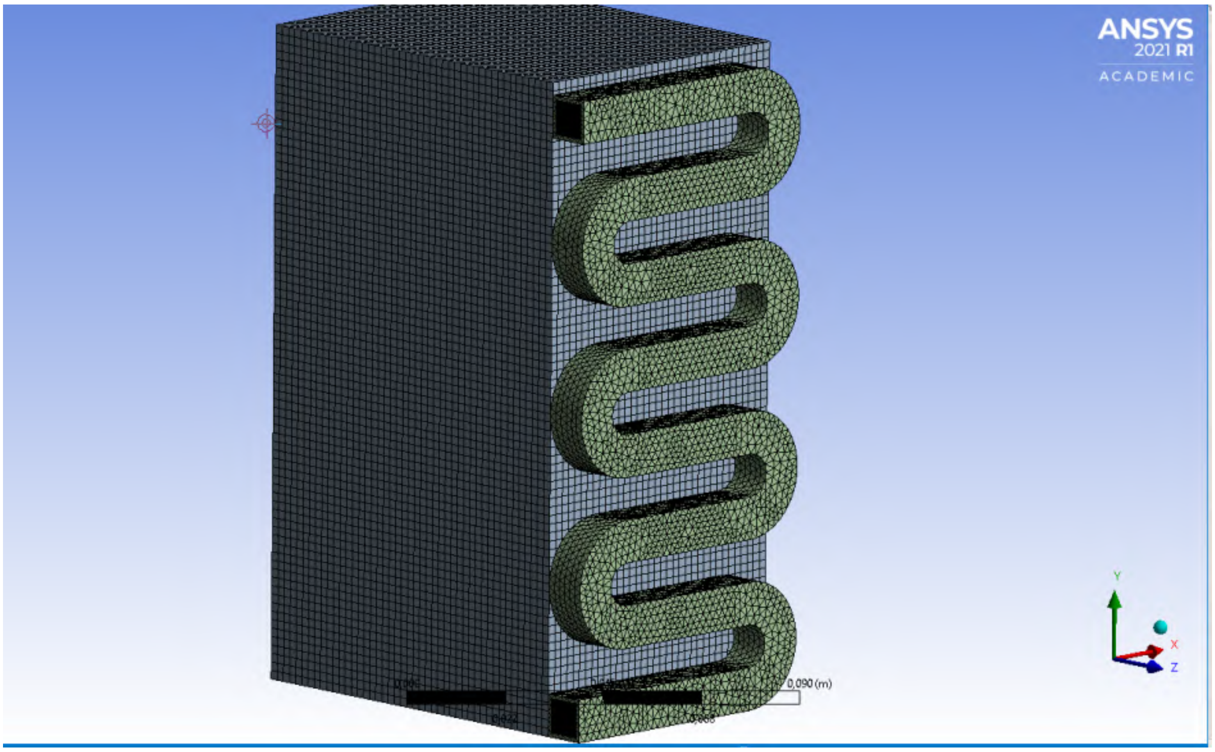


Figure 2.5. Mesh Structure of Design 2

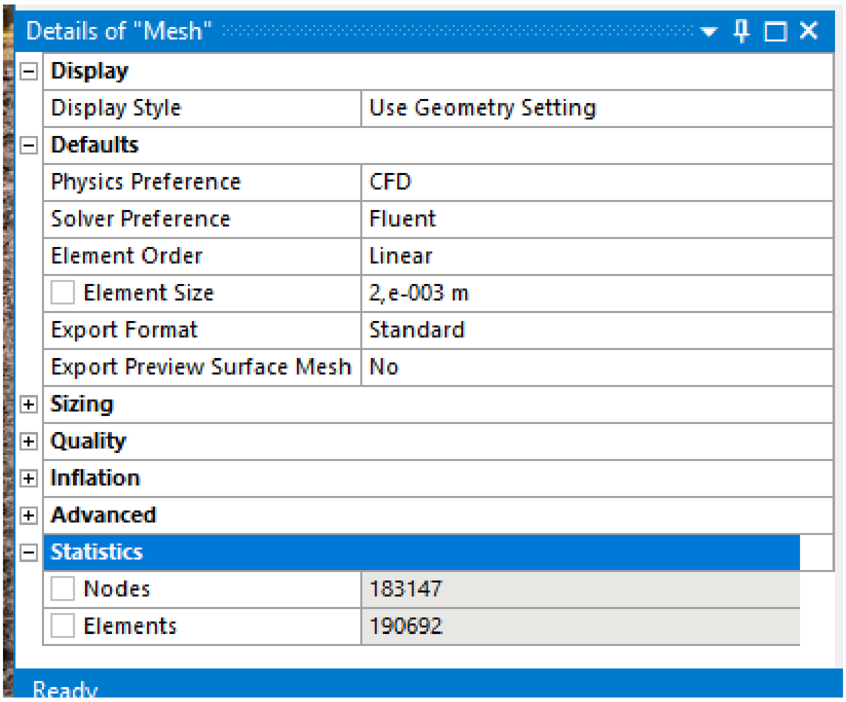


Figure 2.6. Details of Mesh for Design 2

3. ANALYSIS RESULTS AND DISCUSSION

The results of the analysis worked with the boundary conditions of the specified shapes. These results show that the ambient temperature is 300 K, the inlet water temperature is 300 K.

3.1. Analysis Results for Design 1

These results obtained in 600 second analysis. You can see our temperature and pressure analyzes for design 1 on figures below.

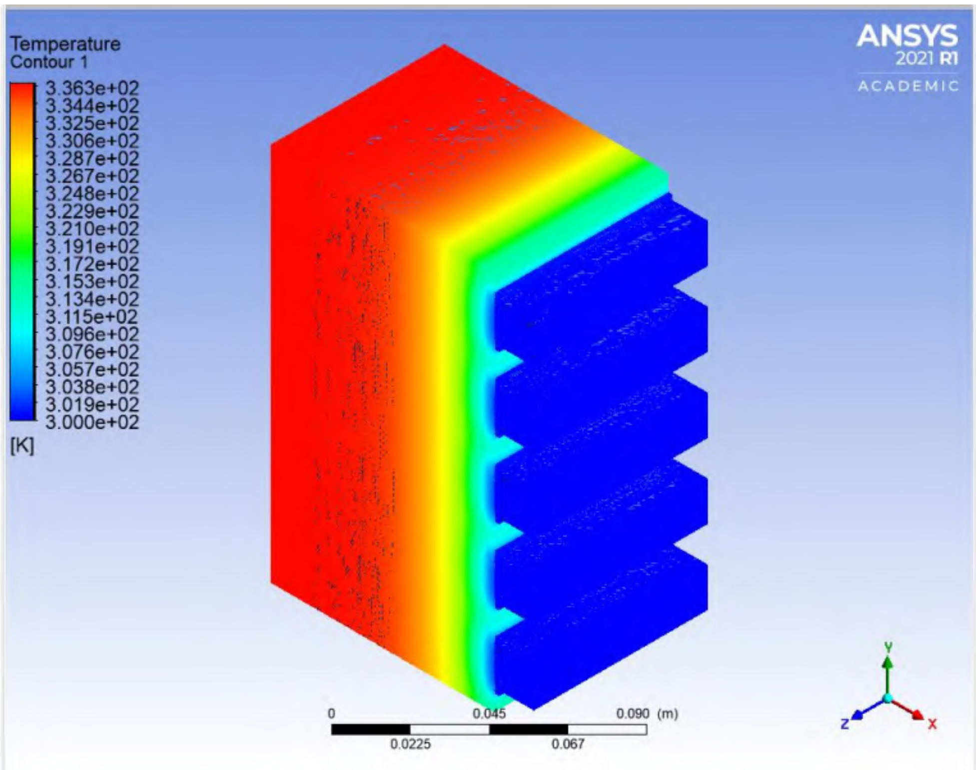


Figure 3.1. Temperature Analysis Result for Design 1

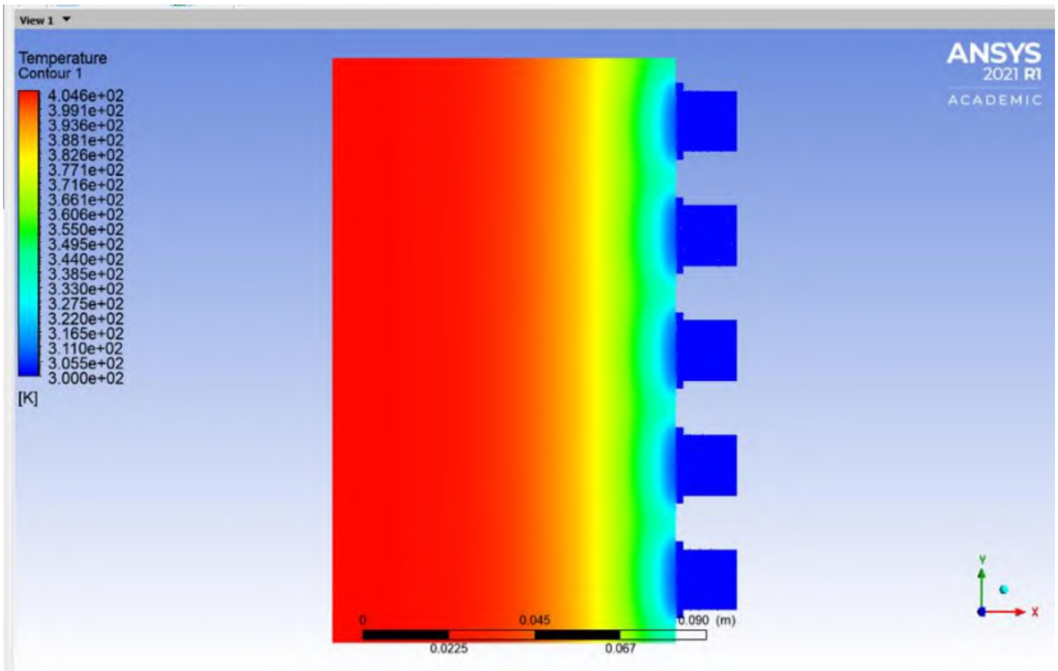


Figure 3.2. Temperature Analysis Result for Design 1 (section view)

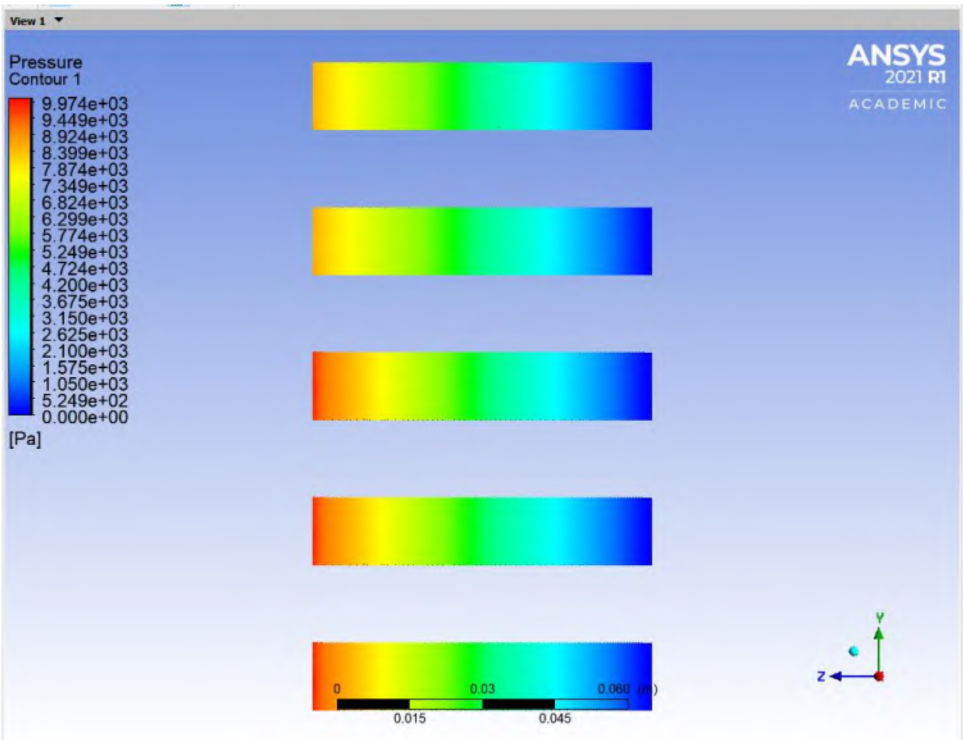


Figure 3.3. Pressure Analysis Result for Design 1 (section view)

3.2. Analysis Results for Design 2

These results obtained in 600 second analysis. You can see our temperature, velocity and pressure analyzes for design 2 on figures below.

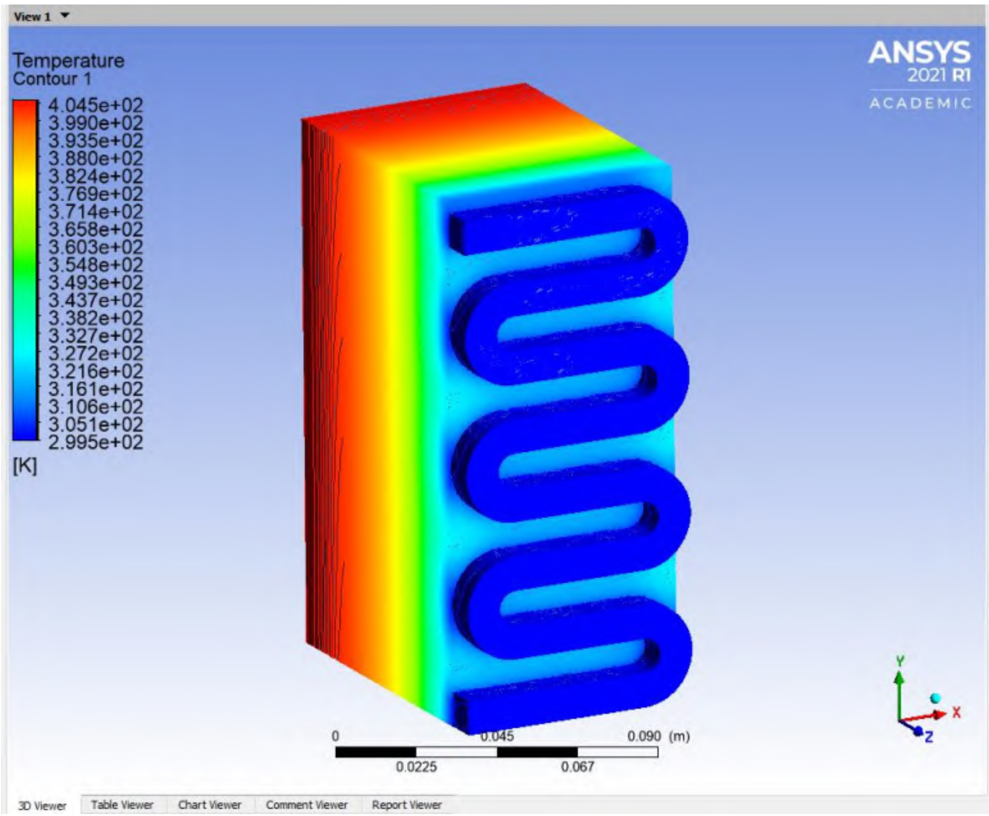


Figure 3.4. Temperature Analysis Result for Design 2

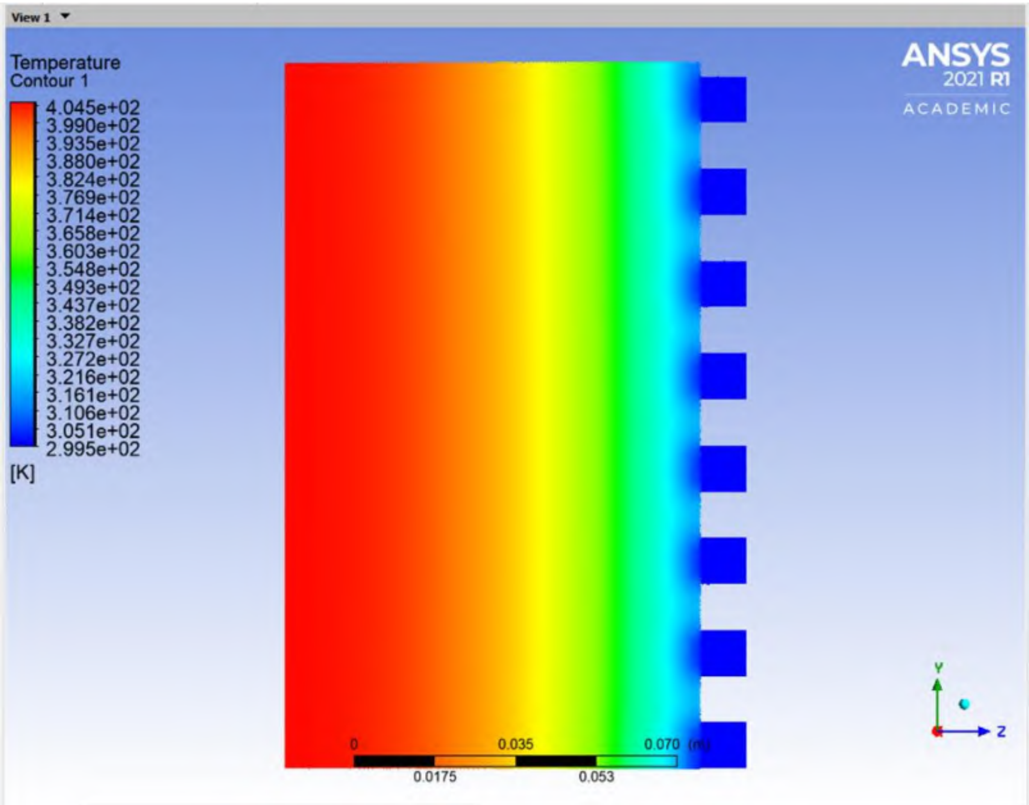


Figure 3.5. Temperature Analysis Result for Design 2 (section view)

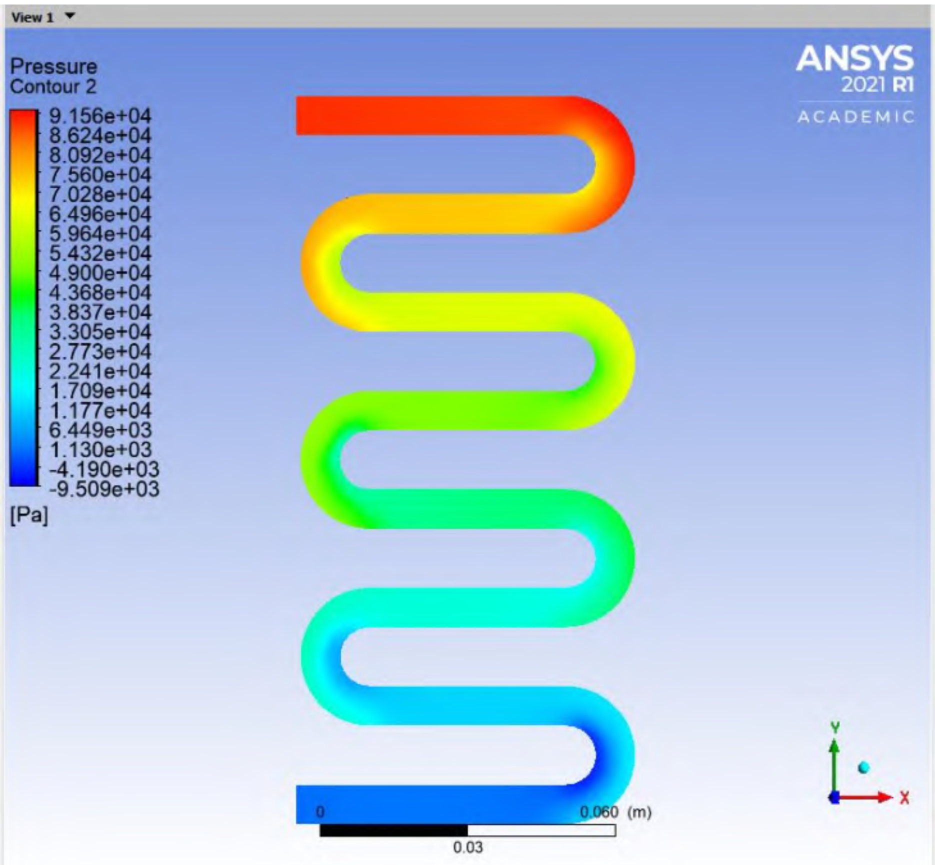


Figure 3.6. Pressure Analysis Result for Design 2 (section view)

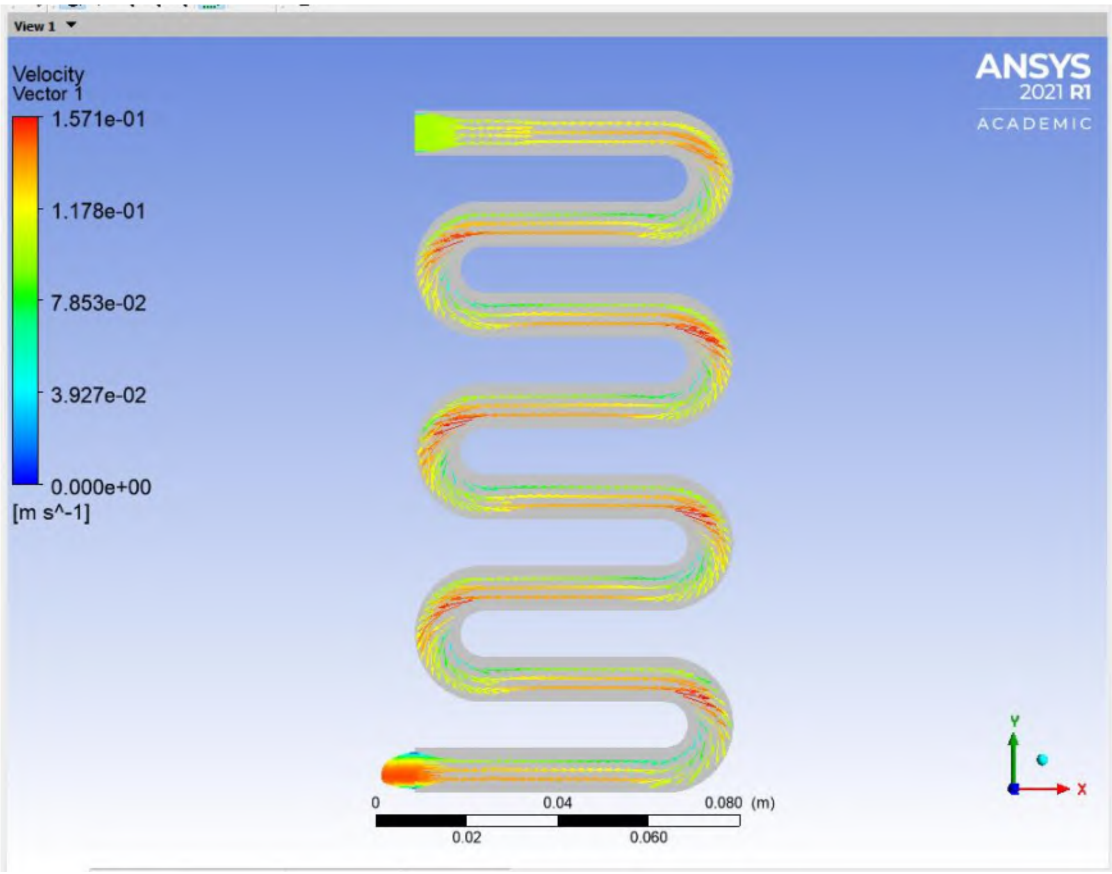


Figure 3.7. Velocity Vector Analysis Result for Design 2

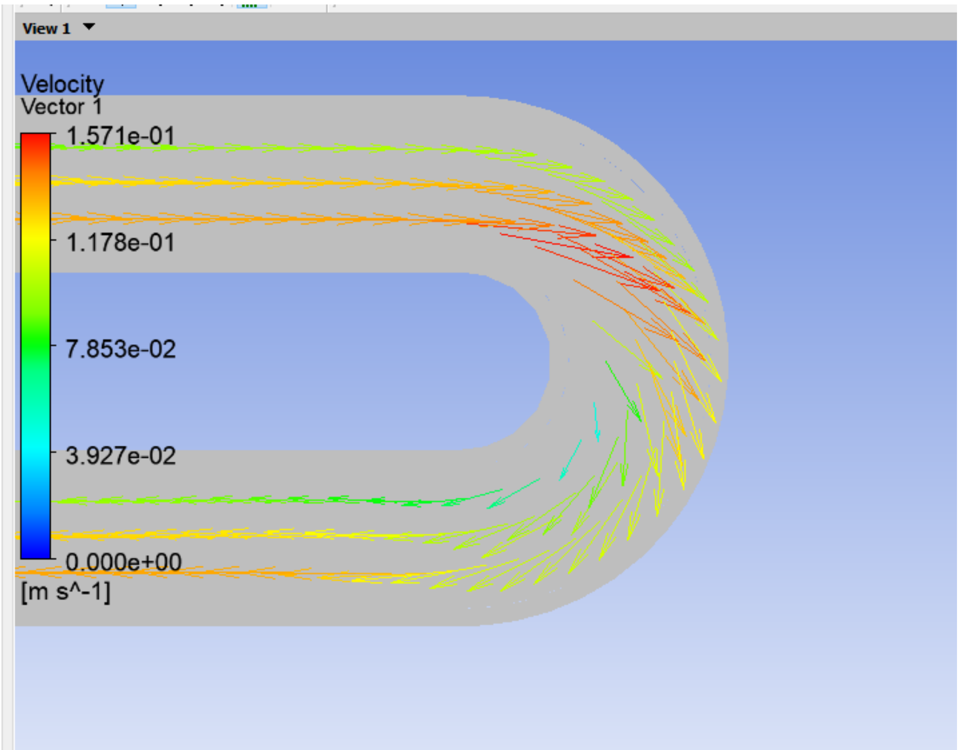


Figure 3.8. Velocity Vector Analysis Result for Design 2 (partial view)

3.3. Comparison of Analysis Results for Design 1 and Design 2

Initially, we obtained different results by varying the water inlet velocity in both designs. The results data is in the table below.

Inlet water velocity (m/s)	Inlet water temperature (°C)	Design 1 Outlet Temperature (°C)	Design 2 Outlet Temperature (°C)	Module Initial Temperature (°C)	Specific point temperature Design 1 (°C)	Specific point temperature Design 2 (°C)
0.1	27	27	27,172	27	43,177	42,996
0.3	27	27	27,139	27	43,116	42,961
0.9	27	27	27,049	27	43,076	42,929
1.5	27	27	27,029	27	43,063	42,919

Table 3.1. Temperature Result Table for Different Velocities

Firstly, we changed the velocities in both designs. We encountered the difference in the water outlet temperature because design 2 has slightly different outlet temperature from design 1. The reason of this difference is the time that water spends in the cooling tube.

Then we specified one point on the battery cells, and we analyzed the temperature in this specific point. Also, there are temperature differences in design 1 and design 2 dependent on different contact area between the cooling tubes and battery cell surfaces.

We did four different analyses in both design by changing the inlet water velocity. In the results we saw that when we increase the inlet water velocity, battery cells temperature decreased because time that water spends in the cooling tube is lower in high velocities.

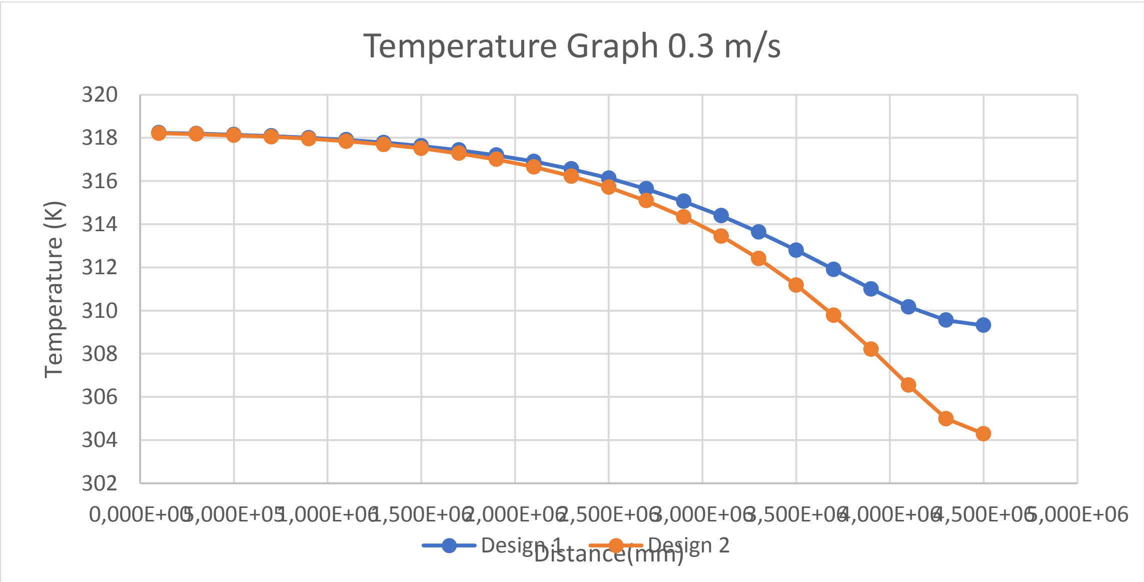


Figure 3.9. Comparison of Temperature for Design 1 and Design 2

This temperature graph shows that a temperature line on the battery cell. We choose the same line geometry in design 1 and design 2. We can look closer to the differences between two design types in this graph.

In second part we changed the inlet water pressure in design 1 and design 2 you can see the results in table below.

Inlet Water Pressure (atm)	Inlet Water Tempera-ture (°C)	Module Initial Temperature (°C)	Specific Point Temperature Design 1 (°C)	Specific Point Temperature Design 2 (°C)	Maximum Pressure Design 1 (Pa)	Maximum Pressure Design 2 (Pa)
1	27	27	43.035	42.899	10074	91560
2	27	27	43.032	42.895	17952	183300
3	27	27	43.030	42.892	27099	274700

Table 3.2. Temperature Result Table for Different Pressures

In this analysis we did not change the inlet water temperature and module initial temperature. We used pressure inlet in setup part of the analysis, and we changed the inlet water pressure three times in both designs. We did not see big differences in battery cells temperature when we changed the inlet water pressure but design 2 is still colder than design 1 because of the difference of the contact area. We observed that when we increased the inlet water temperature, battery cells temperature decreased in both designs because of the time that water spend in the cooling tube. Water spends more time in the design 2.

4. Conclusion

In the future of the automotive industry, the use of electric vehicles will become widespread. The battery pack performance is very important for electric vehicles efficiency. Electrical power provided by the battery pack is affected by many factors. In this thesis we examined the temperature effect on the battery pack. As a result of our research, the operating temperature of the battery pack should be between 10 and 60 degrees. The performance and life of the battery pack is reduced at temperatures outside of this range. As a result of experimental studies on this subject, the temperature range has been narrowed to between 20 and 40 degrees. Taking this study into account, we made a thermal analysis of the battery module through the Ansys program.

First of all, we made two different type 3D design of the battery module in SolidWorks computer program. Our first design has straight channel, and our second design has curved channel. Our first aim was to examine the cooling performance of these two different cooling channels on the battery module. Then we also compared these two designs in terms of changing the velocity and pressure of inlet water. While making these analyzes we specified the ambient temperature, initial temperature of the battery cell and the inlet temperature of the water constant. We set a line on the battery module and evaluated the results on this line.

The first result we encountered is the curved channel has more important role on cooling of the battery module because this design has more contact area. As a result of our analysis, we saw that when we increase the inlet velocity the maximum temperature value in the module decreases also the other result we encountered when we increase the inlet pressure of the water, temperature in the battery module decreased. The reason for these results is the time that water spends in the cooling channels.

As a result of the analysis obtained, the battery designed, and finite element analyzes were made system will work at the desired electrical performance with the water cooling/heating method. In addition to this work, by increasing the quantity of the battery cell studies on the thermal management of the battery pack or the comprehensive battery system can be performed, and different discharge rates can be taken into account as thermal load in the studies. In addition, the studies can be verified with experimental studies and applications.

We did this analysis using only one module of the battery pack but this analysis can be done to the entire battery pack. If it is desired to analyze in different ways, different results can be obtained by the changing water's inlet temperature, velocity, pressure or cooling channel's contact area, width and length. As a result, different results can be obtained from our analysis.

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APPENDICES