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Electrical racing car batteries cooling by air flow: Split University race electrical car case

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Content

1 Introduction ... 9
1.1 Formula student ... 9
1.2 FESB Racing ... 10
1.3 eFRT01 ... 11
2 Research ... 12
2.1 Batteries ... 12
2.2 Phase change materials ... 15
2.2.1 Types of phase change materials ... 15
2.3 Liquid cooling ... 18
2.3.1 Indirect liquid cooling ... 18
2.3.2 Direct cooling method ... 20
2.4 Air cooling ... 20
3 Design ... 23
3.1 Battery configuration ... 23
3.2 Cell characteristics ... 25
4 Simulations ... 30
4.1 First version ... 30
4.1.1 Geometry ... 30
4.1.2 Mesh optimisation ... 31
4.1.3 Setup ... 34
4.1.4 Optimisation ... 38
4.1.5 Results ... 39
4.2 Final version ... 41
4.2.1 Model ... 41
4.2.2 Mesh ... 42

4.2.3 Results..42
4.3 3D model..43
5 Conclusion 44
6 References..45

List of figures

Figure 1 - FRT03 10
Figure 2 - FRM04 11
Figure 3 - Pouch cell Figure 4 - cylindrical cell 13
Figure 5 - Phase change cycle of PCM [3] 15
Figure 6 - Comparison between most used PCMs [4] 17
Figure 7 – PCM Figure 8 - Role of PCM.. 18
Figure 9 - Cooling snake Figure 10 - Cold plate 20
Figure 11 - Air cooling of an EV battery... 21
Figure 12 - Cell specifications [10] 23
Figure 13 - Serial cell connection 24
Figure 14 - Parallel cell connection 24
Figure 15 - Voltage graph 26
Figure 16 - Current graph 26
Figure 17 - Temperature graph 27
Figure 18 - Calorific test setup 29
Figure 19 - Geometry of the module 30
Figure 20 - Geometry of the module 30
Figure 21 - Setup tree 31
Figure 22 - Inflation method 32
Figure 23 - Results of inflation 32
Figure 24 - MultiZone method 33
Figure 25 - Edge Sizing method 33
Figure 26 - Edge Sizing up close 34
Figure 27 - Heat flux of batteries boundary condition 35
Figure 28 - Pressure inlet boundary condition 35
Figure 29 - Intake fan boundary condition 36
Figure 30 - Fan dimensions [12] 36
Figure 31 - Graph given by the manufacturer [12] 37
Figure 32 - Points from the graph in Excel 37
Figure 33 - Fan graph approximated in Excel 38
Figure 34 – Mesh for 1 mm 39

Figure 35 – Mesh for 3 mm 39
Figure 36 - Temperature for 6 mm 39
Figure 37 - Temperature graph for 3 mm 40
Figure 38 - Temperature for 1 mm 41
Figure 39 - Final model.. 41
Figure 40 - Final version mesh 42
Figure 41 - Temperature graph 42
Figure 42 – Battery pack interior... 43
Figure 43 - Battery pack location... 43

Abstract

As electric vehicles become increasingly widespread in the automotive industry, optimizing the thermal management of battery packs has become a critical area of research. This thesis investigates various cooling methods for enhancing the thermal performance of battery packs, with a specific focus on their application in Formula Student vehicles. The study explores passive and active cooling techniques, including air cooling, liquid cooling, and phase change materials. A significant portion of the research is dedicated to the development of an air cooling system, which is favoured in Formula Student vehicles due to its simplicity and low cost. The effectiveness of the air cooling method in dissipating heat and maintaining optimal battery temperature is evaluated through a combination of theoretical analysis and numerical simulations. These simulations were conducted to optimize the spacing between battery cells, starting from 6 mm and narrowing down to 1 mm, to achieve an ideal balance between airflow and space utilization. Additionally, this thesis includes an investigation of different types of battery cells, specifically comparing pouch and cylindrical cells. By simulating various cell layouts, the research aims to identify configurations that maximize thermal efficiency and overall performance. The findings of this thesis contribute to the advancement of battery thermal management systems in Formula Student vehicles, emphasizing energy efficiency, reliability, and adherence to budget constraints. This research supports the ongoing development of competitive and sustainable electric racing vehicles.

Keywords: Air cooling, Formula Student, Electric vehicle, Battery cells, CFD

Abstract

À medida que os veículos elétricos se tornam cada vez mais difundidos na indústria automotiva, a otimização da gestão térmica dos pacotes de baterias tornou-se uma área crítica de pesquisa. Esta tese investiga vários métodos de resfriamento para melhorar o desempenho térmico dos pacotes de baterias, com foco específico em sua aplicação em veículos Formula Student. O estudo explora técnicas de resfriamento passivo e ativo, incluindo resfriamento a ar, resfriamento a líquido e materiais de mudança de fase. Uma parte significativa da pesquisa é dedicada ao desenvolvimento de um sistema de resfriamento a ar, que é favorecido nos veículos Formula Student devido à sua simplicidade e baixo custo. A eficácia do método de resfriamento a ar na dissipação de calor e na manutenção da temperatura ideal da bateria é avaliada por meio de uma combinação de análise teórica e simulações numéricas. Essas simulações foram conduzidas para otimizar o espaçamento entre as células da bateria, começando de 6 mm e reduzindo para 1 mm, para alcançar um equilíbrio ideal entre fluxo de ar e utilização de espaço. Além disso, esta tese inclui uma investigação de diferentes tipos de células de bateria, especificamente comparando células do tipo pouch e cilíndricas. Ao simular várias disposições de células, a pesquisa visa identificar configurações que maximizem a eficiência térmica e o desempenho geral. Os resultados desta tese contribuem para o avanço dos sistemas de gestão térmica de baterias em veículos Formula Student, enfatizando a eficiência energética, a confiabilidade e o cumprimento das restrições orçamentárias. Esta pesquisa apoia o desenvolvimento contínuo de veículos de corrida elétricos competitivos e sustentáveis.

Keywords: Resfriamento a ar, Formula Student, Veículo elétrico, Células de bateria, CFD

1 Introduction

1.1 Formula student

Formula Student competition, organized by the FSAE (Formula Society of Automotive Engineers), is renowned as one of the most prestigious engineering competitions in the world, where students design and manufacture a single-seat race car defined by very strict and precisely defined regulations. Unlike Formula 1, which aims for victory in the race and focuses on the drivers, the emphasis is placed on the technical solutions of the car. In this way, innovation is promoted and students' ability to apply theory learned at university in practice is encouraged. The first competition was held in the early 1980s in the USA and later expanded worldwide – it is now held in over 20 countries, including Croatia since last year.

The evaluation itself consists of static and dynamic parts – static tests are those in which the performance, speed, and durability of the car are not important, instead, the focus is on its background, from logistics, organization, preparation to marketing, production, economic, and business aspects of the entire car and team. They consist of a Cost report, Design report, and Business Plan presentation.

Dynamic tests demonstrate the actual racing value and the final test of the entire design development of the car. They consist of Skid Pad, acceleration race and finally Autocross and endurance race (in which I was a driver on our last competition in Italy). In order for a team to even participate in dynamic tests, it is mandatory to pass a technical inspection conducted by experts from an extremely competent judging panel.

Future of Formula Student is putting emphasis on making cars that are eco-friendly and use the latest technology. Consequently, every year there are fewer combustion electric cars competing because the organisation and sponsors are encouraging the production and development of electric cars. That's where this thesis comes in – it focuses on how to keep the batteries in these electric cars cool while they race. Cooling the batteries is important because it affects how well the car performs, how safe it is, and how long the batteries last.

This thesis looks specifically at using air to cool the batteries, which is simple and budget friendly. By studying different ways to cool the batteries, the aim is to figure out what works best and how it affects the car's performance.

1.2 FESB Racing

FESB Racing is a student team from my home university of Split which I am part of since 2020. We were founded in 2011. and we have made 3 cars and 4 motorcycles since for Formula Student and Moto Student competitions. I personally was a part of 3 projects:

- FRT03 – combustion engine car which went on 2 Formula Student competitions: in Czech Republic we did not pass the static tests, and in Italy last year we finished all the races and placed 5th out of 47 teams.
- FRM 04 – combustion engine motorcycle which went on Moto Student competition in Aragon and was placed 15th because of a crash.
- eFRT01 – our first electric car which is a subject of this thesis

Figure 1 - FRT03

Figure 2 - FRM04

1.3 eFRT01

eFRT01 is our first electric car so we had to do everything from scratch. Starting point was choosing the electric motor and cells that are going to be used. The chosen setup of electric motors is two Emrax 208 motors driving rear wheels. The cells can be of two types: pouch or cylindrical. The difference is going to be researched in the next chapter.

My primary assignment on the project is to develop the cooling of battery pack. Finding it as a quite a big task, I choose it to be my master's thesis. Throughout this thesis, I will explore various cooling methods that can be used to maintain optimal battery temperatures. These methods include using liquids, like water or coolant, air, which surrounds the batteries, and special materials that absorb heat, like phase change materials. While each cooling method has its advantages and disadvantages, I placed the focus on air cooling because it's straight forward, cost-effective, and widely adopted in Formula Student vehicle designs.

2 Research

2.1 Batteries

The project started with choosing the cells that are going to be used and as I was also on that assignment, I will shortly explain the process. There are two main types of cells that can be used:

- Pouch cells
- Cylindrical cells

Cylindrical cells have electrodes wrapped in an aluminium cylinder, with terminals at opposite ends of the cell. The aluminium cylinder provides the necessary pressure on the electrodes inside the cell, eliminating the need for external pressure for optimal performance. They are commonly available in standard sizes, such as 18650 or 21700, which refers to their diameter and height in millimetres (21700 – diameter of 21 mm and height of 70 mm). Advantages of cylindrical cells are: robust construction that the metal casing provides as mechanical protection and ensures the integrity of the cell; cylindrical cells offer relatively high energy density, making them suitable for applications where space and weight are constraints; the tubular design facilitates efficient heat dissipation, which means that they have better thermal management which is crucial for maintaining battery performance and longevity. On the other hand, they have some disadvantages such as: the fixed cylindrical shape may limit design flexibility in certain applications.

In pouch cells, also known as soft-pack cells, the electrodes lie parallel to each other on the same plane, forming a rectangular shape where the terminals are on the same edge of the cell. Pouch cells have a "soft" casing made from a flexible material, such as aluminium or polymer laminate and must be pressed with force from the outside to operate within their ideal performance range. The advantages of pouch cells are: the flat and flexible design which allows easy integration into various device shapes and configurations, maximizing space utilization, also pouch cells are typically lighter than cylindrical cells, making them ideal for applications where weight reduction is a priority and finally the simplified manufacturing process of pouch cells, involving lamination of electrode sheets and pouch sealing, can result in lower production costs compared to cylindrical cells. There are also some disadvantages such as: the flexible pouch casing offers less mechanical protection compared to the rigid metal casing of cylindrical cells, making pouch cells more susceptible to damage from punctures or impacts, also pouch cells may have limited heat dissipation capabilities compared to cylindrical cells, potentially leading to increased thermal stress and reduced battery performance under high-temperature conditions [1].

The difference in energy between these two different types of cells lies in the way manufacturers define the cell's energy. The cell’s capacity can be defined at a 10C discharge, or at a 1C discharge. Therefore, although a cell is specified to have a certain energy by the manufacturer's data, this does not hold true if the cell is discharged faster than the specified 1C. "C-rate" is a term used to describe the rate at which a cell is charged or discharged. For example, a cell may have the same energy of 10.8 Wh, the same nominal voltage of 3.6 V, and a capacity of 3 Ah. However, if they have different C-rates, one has 1C, and the other has 10C, the cell cannot be loaded with the same current.

For example, maximum current of a 1C cell with capacity of 3Ah is $I_{max} = C * [\text{Ah}] = 1 * 3 = 3\text{A}$, and for a 10C cell it is $I_{max} = C * [\text{Ah}] = 10 * 3 = 30\text{A}$

Generally, pouch cells have a higher C-rate than cylindrical cells. Therefore, they can be discharged with a higher current, which is one of the benefits of these cells.

Figure 3 - Pouch cell

Figure 4 - cylindrical cell

Because of obvious security concerns we have decided to use cylindrical cells. After research on which cells would be most suitable for our needs, which are imposed by the rulebook [2] and are limitations on voltage, capacity and weight, we settled on using Molicel 21700 P42A.

The heat of cylindrical cells can be extracted from its poles or the wall. The reason I put it here separately is because they are made from different materials, what means different thermal conductivities. Thermal conductivity is the ability of a material to conduct heat. Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity.

The poles of a battery cell typically refer to the positive and negative terminals where electrical connections are made. These terminals are usually made of metal, such as nickel-plated steel or aluminium. The thermal conductivity of the poles is relatively high compared to other components of the battery cell. Metals, such as steel and aluminium, have high thermal conductivity which is why the poles serve as primary pathways for heat dissipation from the interior of the cell to the external surroundings.

The walls of a battery cell refer to the casing or enclosure that surrounds the internal components, such as the electrodes, electrolyte, and separator. The walls are typically made of materials such as metal alloys or, most commonly, plastic to provide structural support and protection. The thermal conductivity of the walls is generally low er compared to the poles of the cell because plastics have much lower thermal conductivity than steel and aluminium.

Heat transfer through poles and walls are usually called as axial and radial heat transfer. So the batteries have a better heat transfer in axial direction (through the poles). The numbers found in an experimental study are following: radial thermal conductivities varied from 0.15 $\frac{\mathrm{W}}{\mathrm{m}*{}^{\circ}\mathrm{C}}$ to 3.4 $\frac{\mathrm{W}}{\mathrm{m}*{}^{\circ}\mathrm{C}}$, and the axial thermal conductivities varied from 20.06 $\frac{\mathrm{W}}{\mathrm{m}*{}^{\circ}\mathrm{C}}$ to 32 $\frac{\mathrm{W}}{\mathrm{m}*{}^{\circ}\mathrm{C}}$. It says in the study that it is not really reliable because the numbers have high deviations, and the problem is insufficient amount of investigations on the experimental measurement methods of the battery thermophysical properties. Nevertheless, it shows the big difference between axial and radial thermal conductivity [9] .

2.2 Phase change materials

Phase change materials (PCM) absorb heat from their surroundings during the phase transition from solid to liquid, known as melting, and release heat when transitioning from liquid to solid, known as solidification. This ability to store and release thermal energy at a nearly constant temperature makes PCMs valuable for maintaining consistent temperatures within a specified range. During periods of excess heat generation or high ambient temperatures, the PCM absorbs heat from the surroundings, causing it to melt and store the thermal energy as latent heat. When the ambient temperature decreases or cooling demand arises, the PCM releases the stored heat as it solidifies, effectively cooling the surroundings.

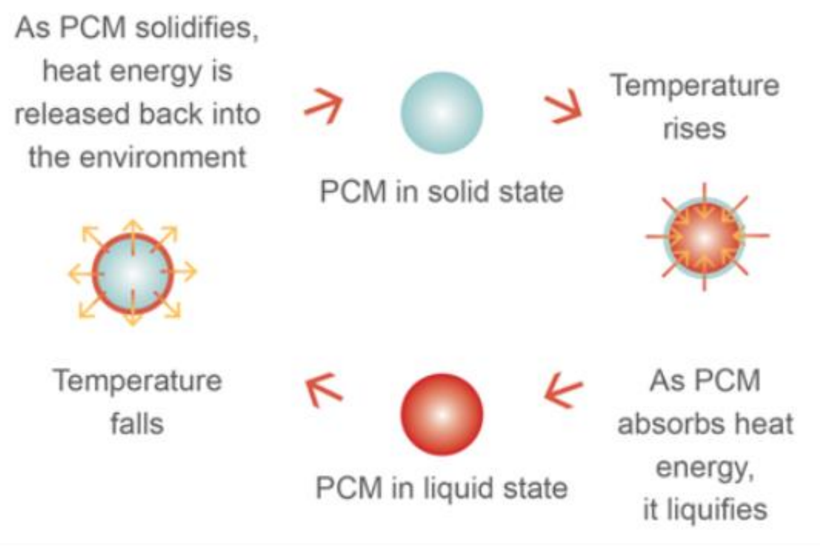

Figure 5 - Phase change cycle of PCM [3]

2.2.1 Types of phase change materials

There are 3 types of phase change materials: organic, inorganic and eutectic.

2.2.1.1 Organic PCM

Organic PCMs are generally categorized into paraffins and non-paraffins compounds. Usually, in this type of materials under repeated melting or solidification cycles, there is no phase segregation. They are not corrosive in nature.

Paraffin wax is one of the most used organic PCMs for thermal management in electronics. It is derived from petroleum or natural sources and is available in various grades with different melting points. It offers advantages such as high latent heat of fusion, wide availability, low cost, and chemical stability. PCM as paraffin has a melting point in the range of 32-38°C which is mixed with graphite flakes to improve thermal conductivity. The graphite flakes will also create a semi-matrix block which will contain the paraffin particles. When the paraffin melts, it stays within this matrix and the whole composition remains as the solid form. Commercial grade paraffin waxes are reported be able to sustain over 1500 cycles while maintaining their properties unchanged. The advantage of solid PCM is that they also act as shields, in case one cell enters a thermal runaway.

The non-paraffin compounds are the most numerous of the phase change materials with a wide variety of properties. They are flammable in nature hence they are not applicable for high-temperature storage. They are also called bio-based PCMs because they are derived from renewable sources such as vegetable oils, fatty acids, or carbohydrates. These PCMs offer environmental benefits and can be tailored to specific temperature ranges. Examples include palm oil, coconut oil, and fatty acid esters [5] .

2.2.1.2 Inorganic PCM

Inorganic PCMs are divided on salt hydrates and metals.

Salt hydrates are the most widely studied PCMs for the latent heat thermal energy storage system, as their melting temperature ranges from 10 to 900 ˚C. Some of their attractive properties are high latent heat of fusion per unit volume, relatively high thermal conductivity, small volume change on melting and higher density. They can undergo phase transitions at relatively low temperatures.

Metallic PCMs are basically a combination of low melting point metals and metal eutectics. Their biggest advantages are high thermal conductivity, very high density, long cycle life, and potential for integration with hydrogen-based energy systems.

2.2.1.3 Eutectic PCM

Eutectic mixtures are composed of two or more substances that form a mixture with a lower melting point than any of the individual components. They solidify without segregation at a temperature that is normally lower than the one at which single components solidifies, called ”eutectic temperature”. Their thermal application is relatively new hence, a limited amount of information is known. They usually have sharp melting points comparable to pure substances and a higher volumetric storage density than organic compounds.

Property or Characteristics	Paraffin Wax	Non-Paraffin Organics	Hydrated Salts
Heat of fusion	High	High	High
Thermal Conductivity	Very Low	Low	High
Melt Temp (•C)	-20 to 100+	5 to 120+	0 to 100+
Latent Heat (kJ/kg)	200 to 280	90 to 250	60 to 300
Corrosive	Non-Corrosive	Mildly Corrosive	Corrosive
Economics	Modern Cost	High Cost	Low Cost
Thermal Cycling	Stable	Elevated Temperature Can Cause Decomposition	Unstable Over Repeated Cycles
Weight	Medium	Medium	Light

Figure 6 - Comparison between most used PCMs [4]

There are parameters that should be considered when using PCMs in battery packs. Higher thermal conductivity allows for better heat dissipation and distribution. The melting temperature range aligns with the desired operating temperature range of the battery pack. High latent heat allows the PCM to absorb or release more energy, thereby more effectively controlling the temperature. The PCM should be stable over multiple heating and cooling cycles to ensure long term reliability. It should be chemically compatible with the battery pack components and materials to avoid any reactions or performance issues. Higher density stores more heat in a given volume [6]. Table of comparison between some types of PCMs is shown in figure 6.

Figure 7 – PCM

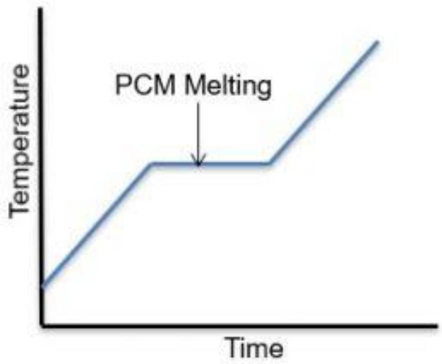

Figure 8 - Role of PCM

2.3 Liquid cooling

Liquid cooling, including both indirect (active) and direct (immersion) cooling methods, is a thermal management technique used to dissipate heat from electronic components, power systems, and other heat-generating devices. It involves circulating a liquid coolant through a heat exchange system or immersing components directly in a dielectric liquid coolant. In the context of electric vehicles (EVs), liquid cooling plays a crucial role in maintaining optimal operating temperatures for battery packs, power electronics, and electric motors.

2.3.1 Indirect liquid cooling

Indirect liquid cooling is the most popular EV batteries cooling technology. It uses a liquid coolant such as water, a refrigerant, or ethylene glycol to cool the battery. The liquid goes through tubes, cold plates, or other components that surround the cells and carry heat to another location, such as a radiator or a heat exchanger. The liquid (water or coolant) has better thermodynamics properties than the air, indeed the heat capacity and the heat conductivity are higher. Components carrying the liquid prevent direct electrical contact between the cells and the liquid coolant to avoid the short circuit issue.

Most used ways of indirect liquid cooling are cold plates and cooling snakes. Difference is that cold plates are extracting the heat from the pole of the cell while cooling snakes are wrapped around the wall of the cell. Both have their advantages: battery cells have much higher thermal conductivity on the poles than on the wall which benefits the cold plate method, but the surface area between the cell and the plate is much smaller than the one when using the cooling snake method. This is shown in the equation bellow [7].

$$Q = k * A \frac{T_2 - T_1}{d}$$

- $\boldsymbol{Q}$ is heat conduction.
- $\boldsymbol{k}$ is the thermal conductivity constant. Different materials will affect the k value.
- $\boldsymbol{A}$ is the contact area. The larger the area, the better the heat conduction effect.
- $\boldsymbol{T_2 - T_1}$ is the temperature change. The heat will go from high temperature to low temperature, so the heat dissipation path can be seen.
- $\boldsymbol{d}$ is the thickness of the material. This affects the speed of heat transfer.

2.3.1.1 Cold plates

Liquid cooling plates are typically constructed from thin layers of thermally conductive materials such as aluminium or copper. They feature an array of internal channels or passages through which a liquid coolant flows. Liquid cooling plates are integrated into the battery pack assembly, with each plate in direct contact with a group of battery cells. This direct contact allows for efficient heat transfer and uniform cooling across the battery pack. The liquid coolant, often a mixture of water and glycol, is circulated through the channels of the cooling plates by a pump. Liquid cooling plates provide precise temperature control, ensuring that battery cells operate within a narrow temperature range. This method is widely used in the car industry because of its light weight and compact design. The plates can be customized to match the specific requirements of different EV models and battery chemistries. They are adaptable to various pack configurations and sizes, providing flexibility in design and integration.

2.3.1.2 Cooling snakes

The cooling snakes consist of flexible or rigid tubes, typically made of materials with high thermal conductivity, such as copper or aluminium. These materials are also lightweight and corrosion-resistant, making them suitable for automotive applications. A liquid coolant, often a mixture of water and glycol, circulates through the internal channels or passages of the cooling snakes. The coolant absorbs heat from the components and carries it away for dissipation. Cooling snakes are integrated into the battery pack and powertrain assemblies of

EVs, with each snake in direct contact with specific components what allows for efficient heat transfer and precise temperature control [8].

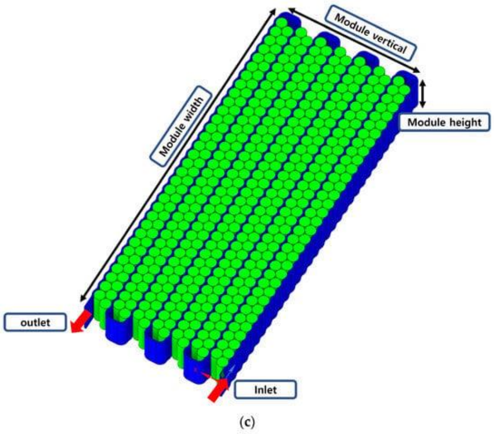

Figure 9 - Cooling snake

Figure 10 - Cold plate

2.3.2 Direct cooling method

Direct cooling, also called immersion cooling, covers the entire surface of the cell, and cools it uniformly. It uses dielectric liquid coolant, such as mineral oil or synthetic fluids, which has excellent heat transfer properties and electrical insulation characteristics. Immersion cooling removes hot or cold spots in the cell and significantly improves the performance of the cell. Ideal coolant must be dielectric with minimum viscosity and high thermal conductivity and thermal capacity. The fluid evaporates to prevent overheating of the cells and avoid thermal runaway. It is widely used for data centre servers and high-power electronics devices, but it is not suitable for most mass-produced electric vehicles due to high cost and safety concerns. It is however used in some high-performing EVs and racing EVs.

2.4 Air cooling

Air cooling relies on the natural or forced convection of ambient air to dissipate heat from the batteries. As components operate, they generate heat, which is conducted through their surfaces and transferred to the surrounding air which passes through the cavities among cells. When the air flows through the cells, it gradually increases its temperature causing the uneven temperature distribution throughout the package. Cells that have different temperatures, discharge in different ways because the efficiency of the batteries is temperature dependent.

This can cause, after a high number of cycles, some batteries to be more ruined than the others. Despite these disadvantages, it is still an attractive solution for applications in which the lightweight and the simplicity is the main goal. It does not need pipes or radiators, hence the weight added with this cooling system is very low. In some variations heat sinks are utilized to increase the surface area available for heat transfer to the air. These heat exchangers may contain fins or other structures to enhance convective heat transfer. Air cooling systems consume less power compared to liquid cooling systems, as they do not require pumps or additional energy to circulate coolant. This contributes to overall vehicle energy efficiency.

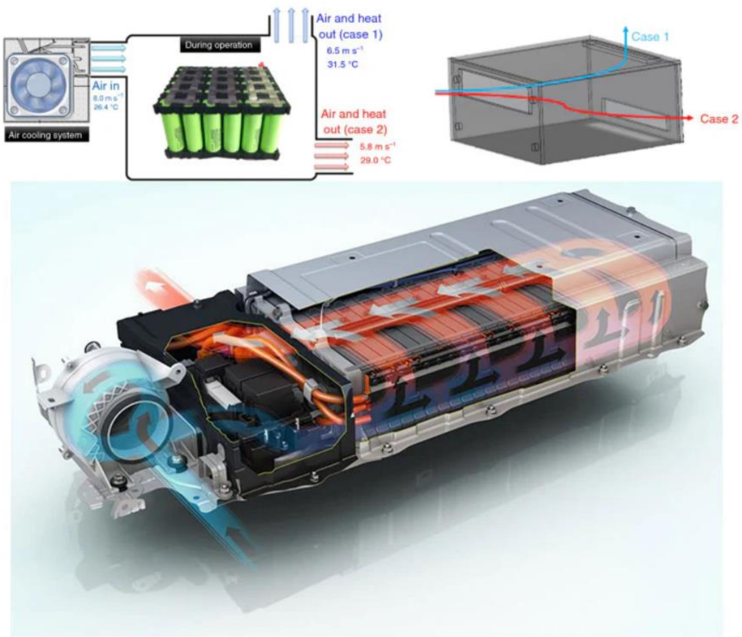

Figure 11 - Air cooling of an EV battery

Air cooling can be of active or passive type. Passive air cooling uses natural air from outside to cool or warm the battery. The amount of air that enters the battery pack depends on the speed with which the car is moving. It's simple but has its limitations and it can only handle a small amount of heat. Important thing in both passive and active air cooling are air ducts. Air ducting channels airflow from the front of the vehicle to the batteries and directs the heated air away from the vehicle. Ducting may include vents, baffles, and other structures to optimize airflow distribution and minimize aerodynamic drag.

Active type of cooling needs fans to push the air through the pack. It can be done with fans that are pushing the air through or the ones that are pulling the air from the pack. Cooling fans are essential components of air cooling systems in EVs. They generate airflow over the heat-generating components, promoting heat dissipation. Fans may be driven by electric motors and controlled by temperature sensors or vehicle management systems. It can have heat exchangers that can cool or heat the air that is entering the battery pack depending on the needs. Optimizing the airflow through the pack is done with changing the way that the cells are positioned.

Considering that Formula Student cars are not moving at very high speeds and the competition is in the summer, passive method is not an option. Active method is chosen because of its simplicity, reliability, and low cost [6].

3 Design

3.1 Battery configuration

The construction of the battery pack is greatly dependent on the rules from the official Formula Student rulebook [2]. Those rules, according to Formula Student rulebook EV5.3 are:

- Maximum open circuit voltage of the tractive system energy storage is 600 [VDC]
- Maximum open circuit voltage of the energy storage module is 120 [VDC]
- Maximum energy stored per module is 6 [MJ] [1.66kWh]
- Maximum weight of each module is 12 [kg]

From my colleague's Open Lap simulations, I got the needed capacity of 8 kWh. With capacity, rulebook restrictions and the specifications of the cell (figure 11.), battery pack can be designed. To be able to optimize the layout of batteries, firstly the configuration of how they are distributed in series and parallel connection has to be determined.

■ CELL CHARACTERISTICS

Capacity	Typical	4200 mAh 15.5 Wh
	Minimum	4000 mAh 14.7 Wh
Cell Voltage	Nominal	3.6 V
	Charge	4.2 V
	Discharge	2.5 V
Charge Current	Standard	4.2 A
Charge Time	Standard	1.5 hr
Discharge Current	Continuous	45 A
Typical Impedance	AC (1 KHz)	10 mΩ
	DC (10A/1s)	16 mΩ
Temperature	Charge	0°C to 45°C
	Discharge	-40°C to 60°C
Energy Density	Volumetric	615 Wh/l
	Gravimetric	230 Wh/kg

Figure 12 - Cell specifications [10]

In a series connection, the positive terminal of one battery cell is connected to the negative terminal of the next cell, and so on, creating a chain-like configuration. When cells are connected in series, the voltages of individual cells add up. The same current flows through all cells in a series connection. This means that the capacity (ampere-hours) of the battery pack remains the same as that of a single cell, while the voltage increases. Series connections are commonly used to increase the voltage of battery packs for applications such as electric vehicles, where high voltage is required to power the motor.

Figure 13 - Serial cell connection

In a parallel connection, all the positive terminals of the battery cells are connected, as are all the negative terminals, resulting in a parallel configuration. When cells are connected in parallel, the capacities (ampere-hours) of individual cells add up. The voltage remains the same as that of a single cell in a parallel connection. However, the capacity increases because more cells are available to provide current. Parallel connections are commonly used to increase the capacity of battery packs for applications such as energy storage systems, where high capacity is required to store energy for later use.

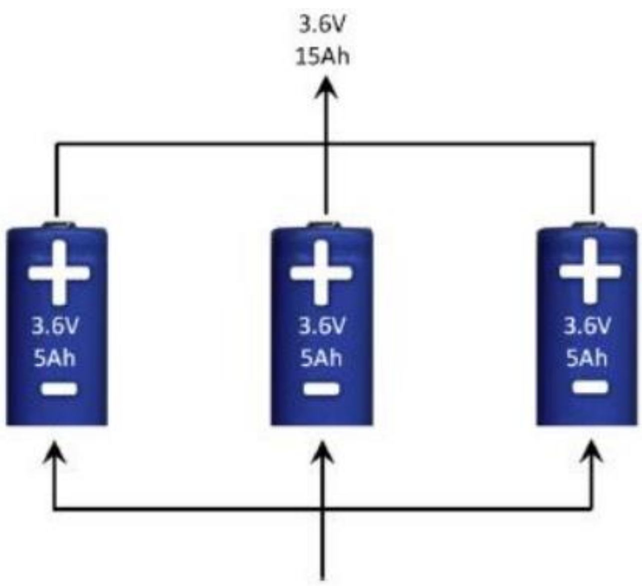

Figure 14 - Parallel cell connection

If the maximum open circuit voltage of the pack is 600 V, and the maximum voltage of the cell is 4.2 V than, knowing what is said in the last two paragraphs, the maximum number of cells that can be connected in series is $600\text{ V}/4.2\text{V} \approx 142$. Next restriction is that the maximum energy stored per module is 6 MJ or 1.66 kWh. That will restrict the number of parallel connections. If we need 8 kWh and the restriction per module is 1.66 kWh, then we have to find a number of parallels using what we learned in the last paragraph that will satisfy that. Calculation $1.66\text{ kWh} * 5 = 8.3\text{ kWh}$ confirms that 5 parallel connections will satisfy the restrictions and our need of 8 kWh. To determine the number of cells in series that we can actually use we have to look at the capacity of a cell. The capacity of the cell is $4\text{ Ah} * 4.2\text{ V} = 16.8\text{ Wh}$. To satisfy the restriction of maximum 1.66 kWh we settled for 95 cells in series in one module. In conclusion there are 570 cells in the pack, distributed in 6 modules so the configuration of the pack is 114s5p.

3.2 Cell characteristics

Before going into simulations all the data for the cell needs to be known. Dimensions of the cell are stated in the datasheet, number of cells is determined, thing left is to find the heat flux of the cell because the simulations require that data. To calculate the heat flux two things need to be familiar, heat dissipation of the cell, and the area through which the heat is dissipated. For the surface area, the surface of the wall of the cell was taken because only that part is in direct contact with air while the poles are covered with electrical connections and the plastics cells holder. Diameter of the cell is 21 mm and height is 70 mm so from the equation down below the surface area of the wall is calculated.

$$A = 2 * r * \pi * h = 2 * 0.0105 * \pi * 0.07 = 0.0046\text{ m}^2$$

Now the heat dissipation is needed. It is determined experimentally on a test bench made in the garage. The purpose of the test bench is to try to simulate discharging of the cell as close to the realistic way that it is discharging during the race. The graph of discharging is taken from Open Lap simulation and the next thing is to try to simulate it. The battery is connected in a circuit with a relay, resistor and an Arduino. The system is programmed to periodically turn the current flow on and off, so it resembles the current through the pack in a race. That results in the current flow being allowed for 47% of the time. Initial voltage of the cell is 3.5V and initial current is 27.8A. Voltage, current and temperature are measured every 30 seconds. Test was supposed to last for 20 minutes. Initial temperature of the battery was 22°C and initial ambient temperature was 21.4°C. Test lasted for 16.5 minutes because the temperature came close to 60°C which the cells should not go over. Voltage, current and temperature change is showed in next few graphs with seconds showed on the horizontal axis.

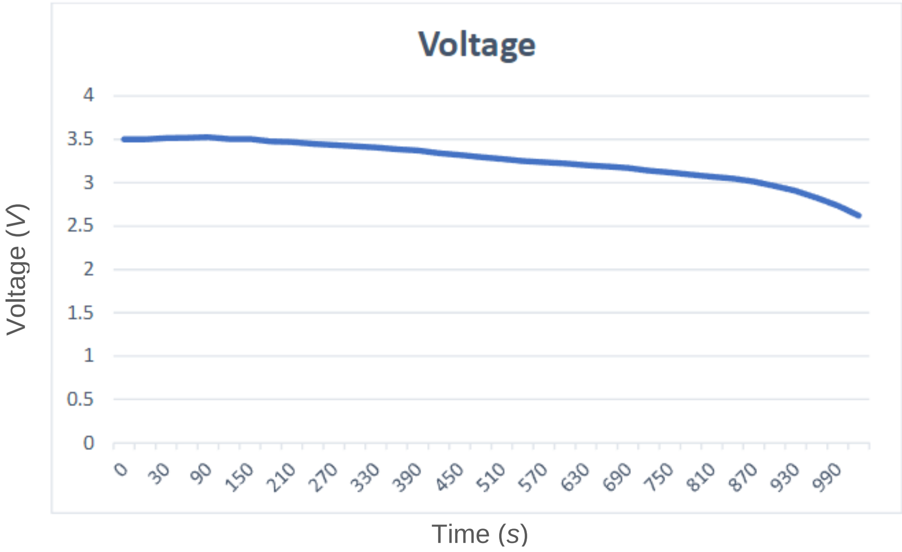

Figure 15 - Voltage graph

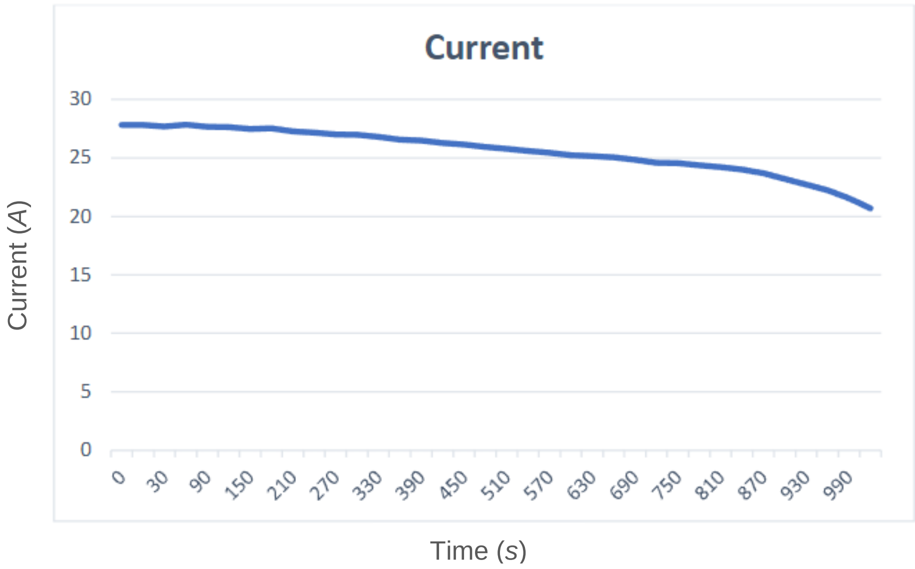

Figure 16 - Current graph

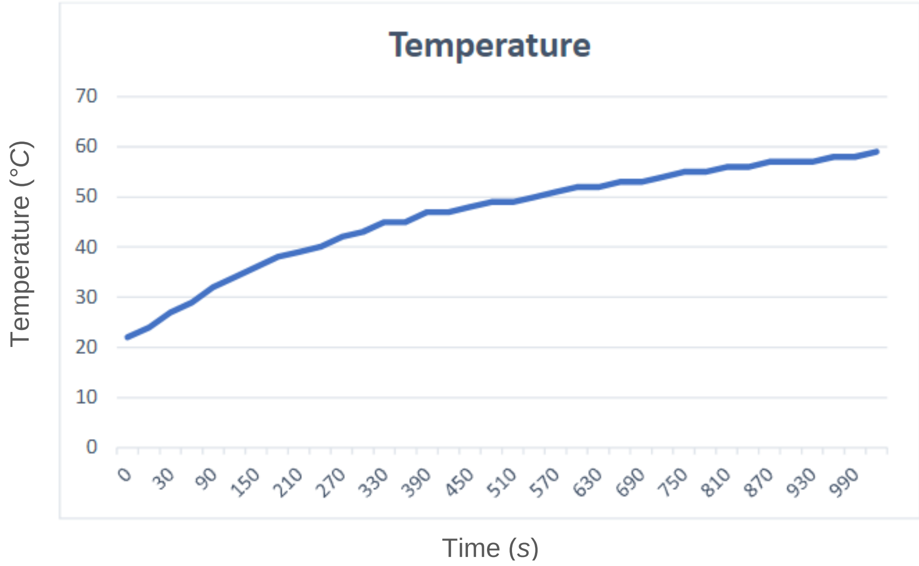

Figure 17 - Temperature graph

Test showed that the temperature of the cells almost got to 60°C which is the temperature it should not exceed, that proves that it has to have a cooling system. Knowing that the resistance is 16 mΩ from the datasheet in figure 11, and now having the graph of the current during the discharging, power can be calculated with the equation below.

$$P = \int_0^t I^2 * R$$

Integral is used because the current changes over time because the system is programmed the way that it allows current flow so that it simulates the race in reality, when the driver is pressing and releasing the throttle. Considering that the average square of the current during the given 30 seconds is equal to the square of the current measured at the beginning of the given interval multiplied by the factor of 0.47 because, as it was said before, the current was flowing for 47% of the time so it simulates reality. That calculation was done in excel and the calculated heat dissipation is 4.98W. Because of possible errors in simulation and considering that the connections between cells will also generate some heat, factor of security was taken into account and fluid flow simulations are going to be done with heat dissipation of 6 W per cell.

Knowing the heat dissipation of the cell and the surface area from which the heat is dissipated heat flux can be calculated. Heat flux, sometimes referred to as thermal flux, is a flow of energy per unit area and per unit time. It is typically measured through a solid surface, as in the case of conduction heat transfer. It can also be measured at a fluid-solid boundary; this is typical of a convective heat transfer analysis. In other words, it quantifies the amount of heat transferred through a surface in a specific direction. The SI units of heat flux are Watts per square meter (W/m^2). In this case heat flux is heat dissipation dependent on time divided by surface area. Simulation is going to be done with heat flux of 1320 W/m^2.

Other data about the cell that are needed for the simulation are cell density and specific heat capacity. Cell density is easily calculated from volume and mass of the cell. Mass of the cell Is 70 g and the volume of the cell is $24245.24\ \mathrm{mm}^3$ or $2.42 * 10^{-5}\ \mathrm{m}^3$. From that density turns out to be $2893\ \ \mathrm{kg/m}^3$.

Specific heat capacity was determined with a calorific test. Thermistor was glued to the cell and it was cooled to 0 °C. After that it was submerged in the thermally isolated container filled with water at the temperature from the tap which was 18 °C. Other thermistor was submerged in water. Changing of temperatures was tracked and written in Microsoft Excel document until the temperatures of the cell and water were equal. Mass of the water in the container was 150 g, temperature difference from start to finish was 1.5 °C, and the specific heat capacity of water is $4186\ \ \mathrm{J/kg°C}$ [11].

$$Q = m * c * \Delta T$$

From the equation above, using the data for water that are previously mentioned, heat absorbed by the water is calculated and it equals to 948129 J. Considering that the container is well isolated, all the heat that was absorbed by water was released from the cell so heat equations for the cell and water can be equated. By changing the equation so it calculates the specific heat capacity, it can be determined for the cell. Mass of the cell is 70 g and temperature difference from beginning to end was 16 °C. It was calculated that the specific heat capacity of the cell is around $850\ \ \mathrm{J/kg°C}$.

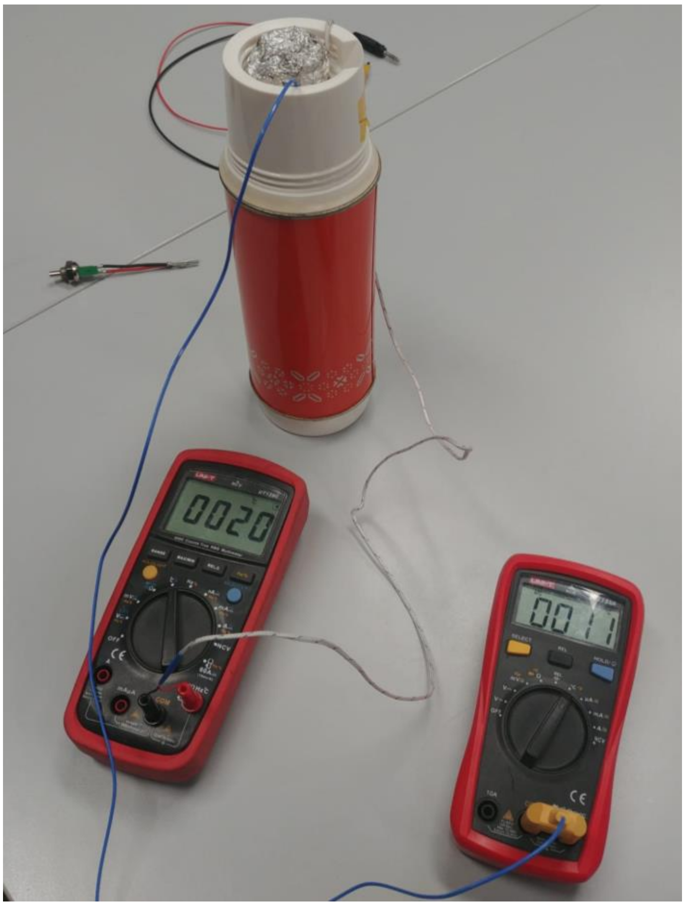

Figure 18 - Calorific test setup

4 Simulations

4.1 First version

4.1.1 Geometry

The simulations are done in Ansys Fluent, and geometry is modelled in Design modeler part of Ansys. Only one module is modelled, and the simulations are done through only one module. Sections before and after the module are about five times longer than their height so air flow can become as realistic and steady as possible before it reaches the cells. That is done so the program has less trouble with solving.

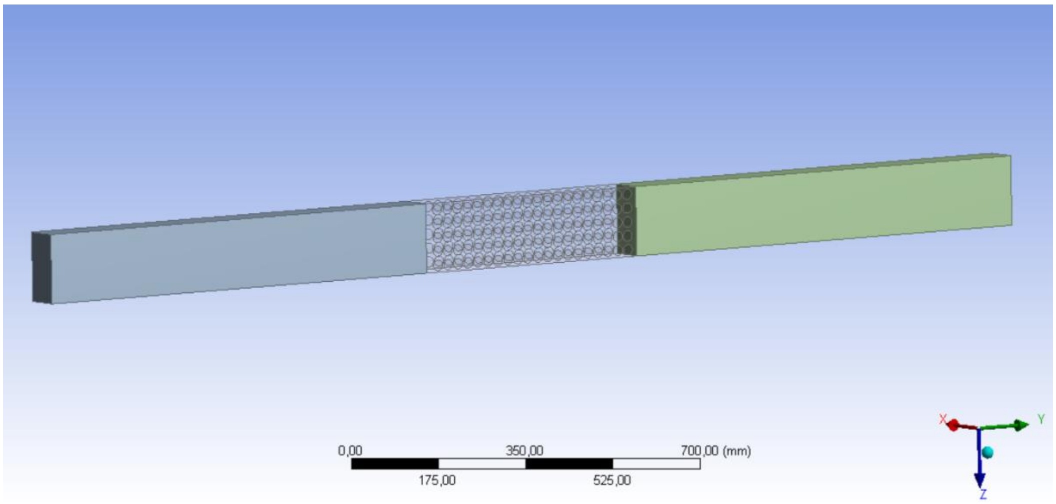

Figure 19 - Geometry of the module

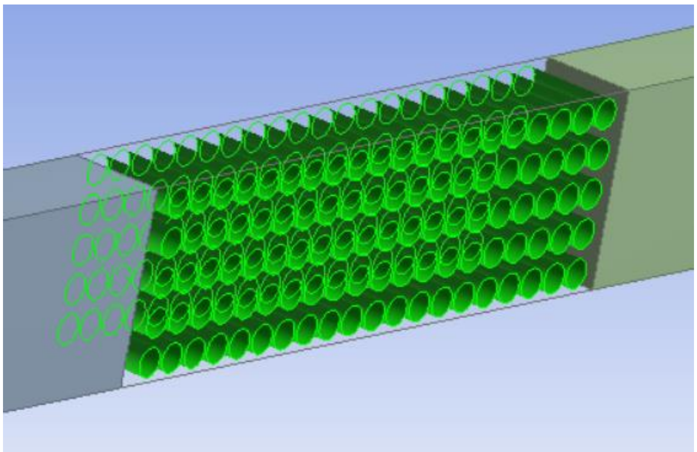

Figure 20 - Geometry of the module

4.1.2 Mesh optimisation

First, it is necessary to create an optimal mesh, one that would yield the most accurate results but with as few elements as possible to shorten and simplify the simulation. In computational fluid dynamics (CFD) simulations, mesh quality plays a critical role in achieving accurate and reliable results. Ansys Fluent provides various mesh optimizing methods to refine and control the mesh, ensuring it meets the specific requirements of the simulation. Initially, simulations were performed with 1,452,766 elements, then with 623,952 then with 363,990, and 148,564 elements. Ultimately, the option with 363,990 elements is chosen because this configuration provided the same results as simulations with more elements, while simulations with fewer elements produced worse and not consistent results. Mesh optimisation methods used are *Inflation*, *MultiZone* and *Edge Sizing*.

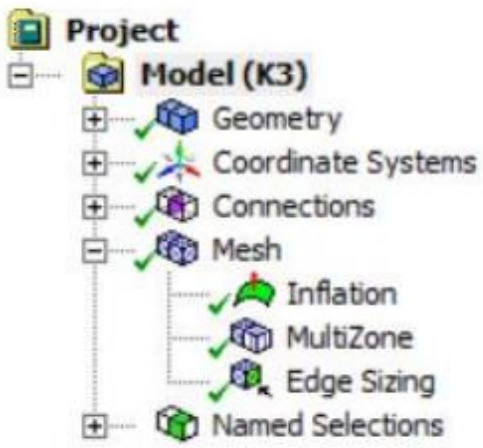

Figure 21 - Setup tree

Inflation is a meshing technique used to create layers of highly refined elements near boundaries, such as walls, to accurately capture boundary layer effects. This is particularly important in simulations involving fluid flow where near-wall gradients are significant. Purpose is to accurately resolve the boundary layer and near-wall regions where gradients in velocity, temperature, or other variables are steep. It improves accuracy in capturing boundary layer phenomena, enhanced resolution of flow gradients, and better overall solution accuracy.

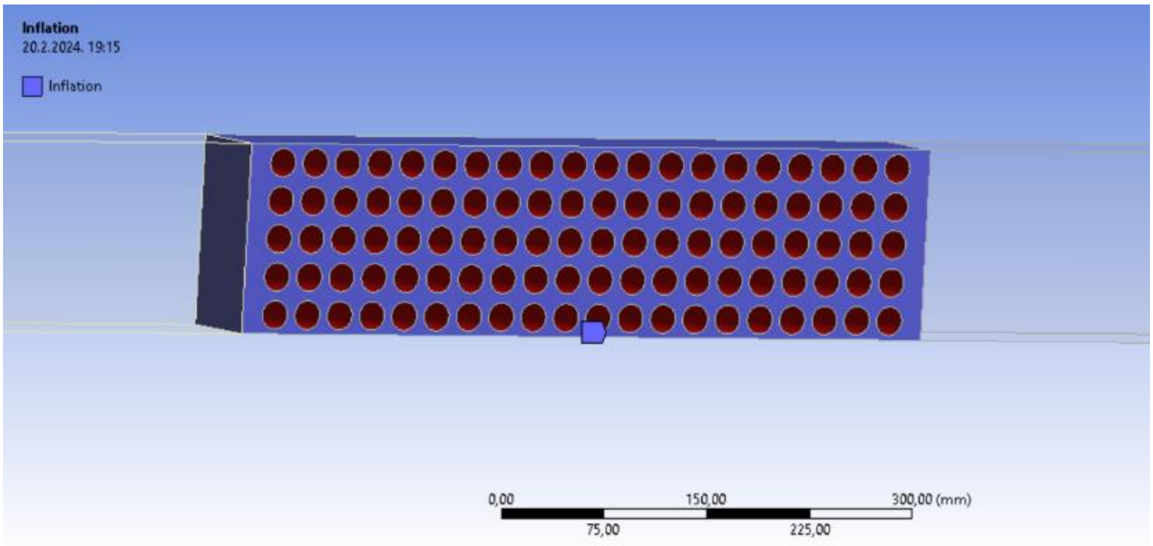

Figure 22 - Inflation method

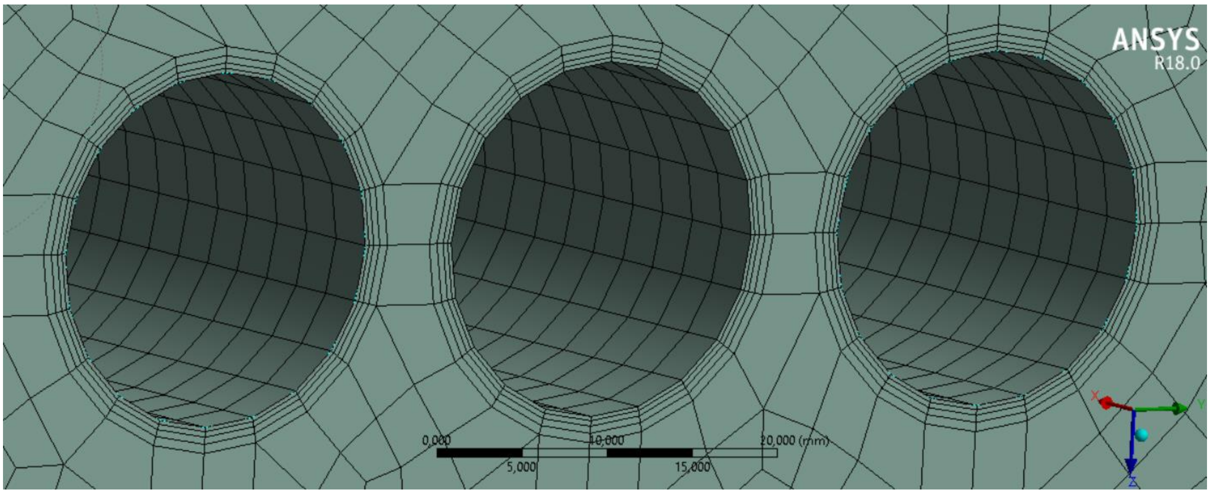

Figure 23 - Results of inflation

Multi Zone meshing is used to create structured or semi-structured meshes in complex geometries by dividing the domain into several zones, each of which can be meshed independently. This method is useful for balancing the need for mesh quality and computational efficiency. Purpose is to generate high-quality structured meshes in geometrically complex domains and to control mesh density in different regions. Its benefits are greater control over mesh quality and density, ability to use structured meshes where beneficial, reduced computational cost, and improved mesh quality in complex geometries.

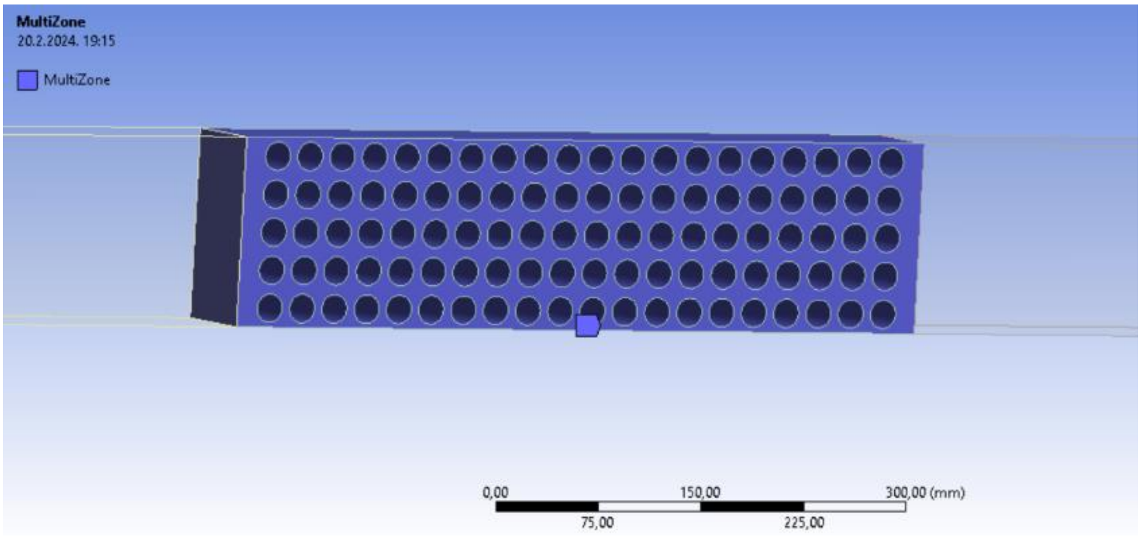

Figure 24 - MultiZone method

Edge Sizing is a method to control the size of the elements along specific edges of the geometry. This allows for localized mesh refinement and improved control over element distribution. Purpose is to achieve refined mesh in regions of interest or along critical edges, ensuring that the mesh density is appropriate for capturing important features of the flow. It is implemented by giving the program some boundaries. With edge selection, specific edges of the geometry are selected for refinement. After that the desired element size along the selected edges is specified. Bias Factor controls the distribution of element sizes along the edge, allowing for a gradual change in element size. Finally, number of divisions is given which specifies the number of elements along the edge. Advantages are enhanced control over local mesh density, improved resolution of geometric features, and better capturing of gradients along edges.

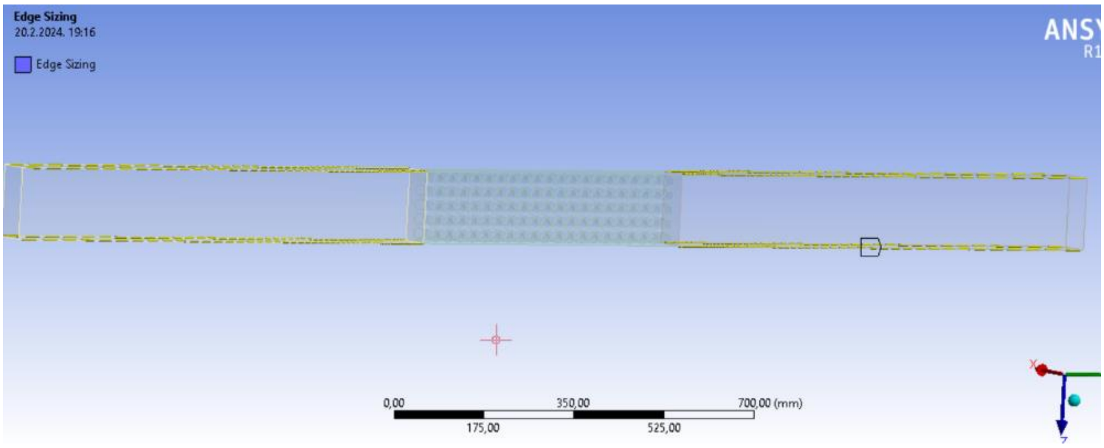

Figure 25 - Edge Sizing method

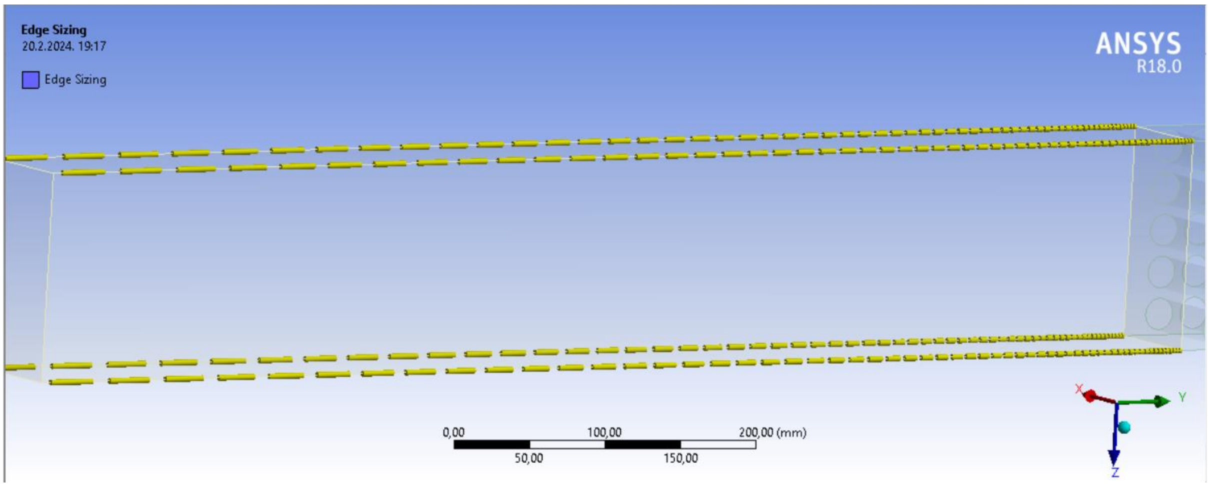

Figure 26 - Edge Sizing up close

Mesh optimization in Ansys Fluent using Inflation, Multi Zone, and Edge Sizing methods provides significant benefits in terms of accuracy and efficiency of CFD simulations. By carefully controlling mesh density and distribution, these methods help in resolving critical flow features and ensuring high-quality solutions. Proper application of these techniques is essential for obtaining reliable and accurate results in various engineering simulations.

4.1.3 Setup

There are many simulation models to choose from but for this project SST k−ω model is used. The SST k−ω model is designed to provide accurate predictions of flow characteristics, particularly in areas with negative pressure gradients and separation. It is widely used for a variety of engineering applications including aerodynamic analysis, turbomachinery, and heat exchangers. The SST model uses a blending function to transition between the k−ω model in the near-wall region and the k−ϵ model in the free stream. This approach takes advantages of both methods in one: the near-wall accuracy of the k−ω model and the robustness of the k−ϵ model in the far field. It is robust and versatile meaning that it is suitable for a wide range of turbulent flows, including those with strong negative pressure gradients and separation.
It consists of two key components: turbulence kinetic energy (k) which represents the energy in turbulent fluctuations and specific dissipation rate (ω) which represents the rate at which turbulence kinetic energy is converted into thermal energy.

The program needs to know material specifications. Air and aluminium (the module housing is made of aluminium) specifications are taken from Ansys database. Battery cell material specifications are put manually. How the numbers were determined is explained in section 3.2.

Locations of boundary conditions are shown in figures 27, 28 and 29. For air intake the boundary condition pressure inlet is used. Everything is left as default in it because it only says that there are atmospheric conditions. To simulate batteries giving heat, wall boundary condition is used named batteries heatflux. It is placed on the surface of the battery wall, and it is defined as a stationary wall with heat flux of 1320 W/m^2 which was also calculated in section 3.2. Also, wall thickness option of 0.01 m was used (the radius of the cell) to simulate that the calculated heat is coming from the centre of the cell and not di rectly from the surface.

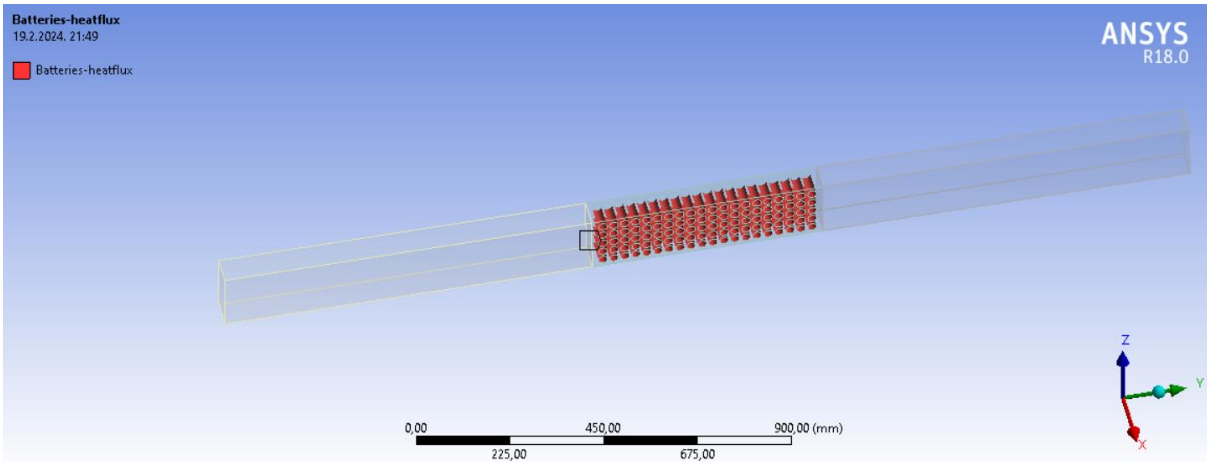

Figure 27 - Heat flux of batteries boundary condition

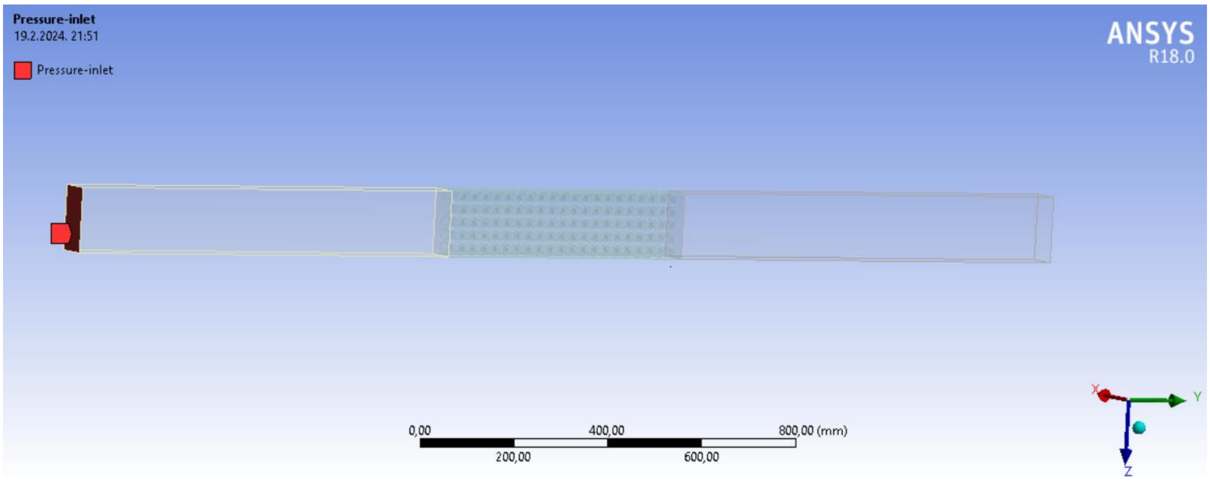

Figure 28 - Pressure inlet boundary condition

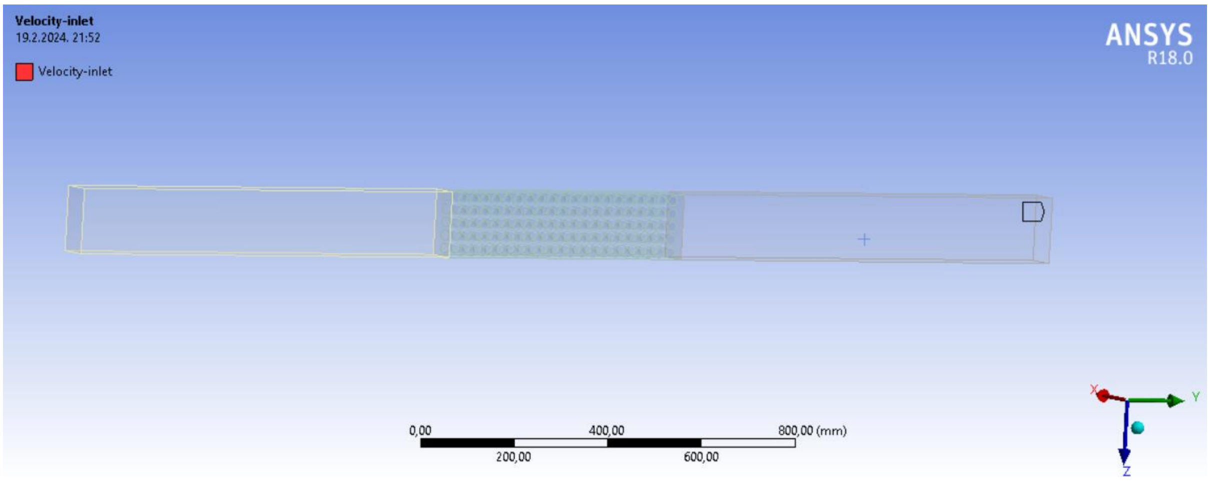

Figure 29 - Intake fan boundary condition

The last boundary condition is on the exit of the module and it is *exhaust fan*. It defines pressure jump as a polynomial function of temperature. It is on the exit of the module because the first idea was that the fan will be on the exit and it will suck out the air from the module. The fan was defined in a way that the exact fan that was available in the garage already and should meet our requirements was found on the website of the manufacturer. The manufacturer provides a graph showing the relationship between pressure drop and volumetric flow rate. This graph is drawn in Excel to derive the polynomial equation that needs to be input into Ansys. Since the program encounters some issues when calculating with a high-degree polynomial, the graph was approximated with a first-degree polynomial, as it sufficiently approximates the curve for accuracy requirements.

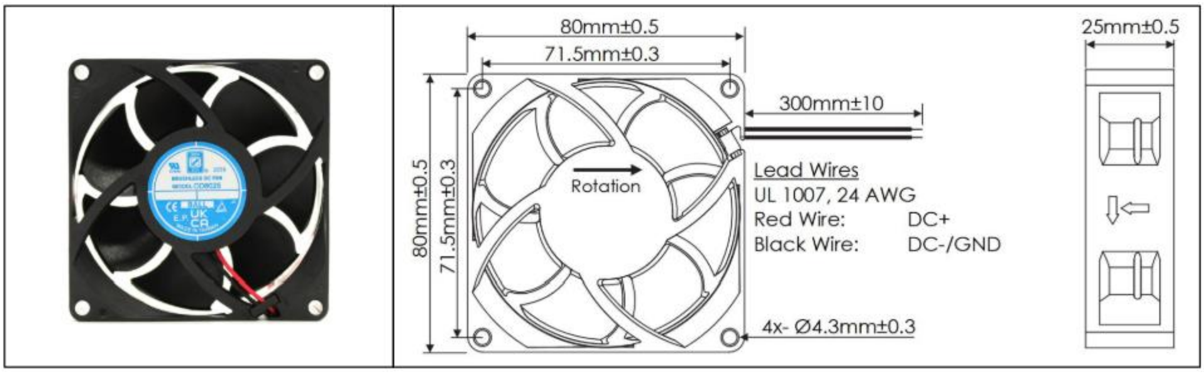

Figure 30 - Fan dimensions [12]

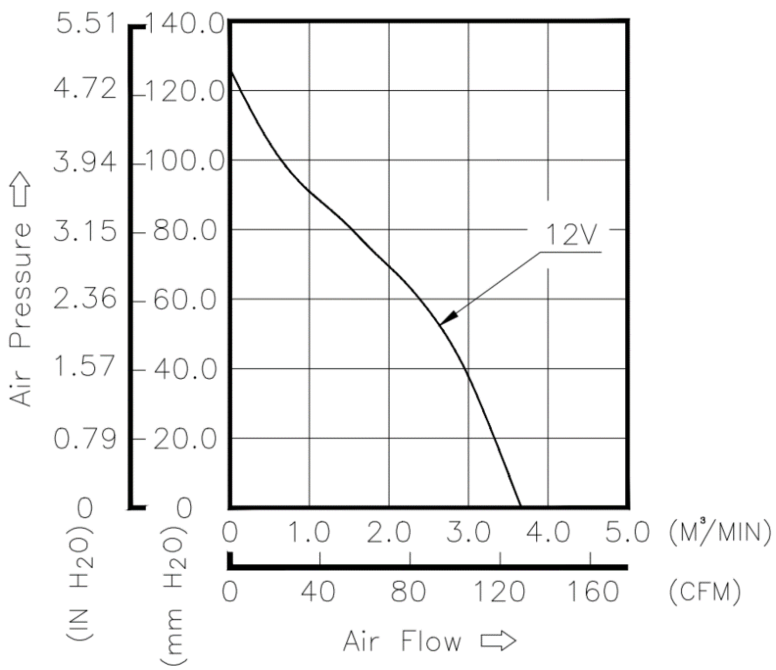

Figure 31 - Graph given by the manufacturer [12]

m3/min	m/s	Pa	mmH2O
0	0	1235.64	126
0.6	1.98944	980.665	100
1	3.31573	892.405	91
1.5	4.97359	784.532	80
2.4	7.95775	588.399	60
3	9.94718	382.459	39
3.7	12.2682	0	0

Figure 32 - Points from the graph in Excel

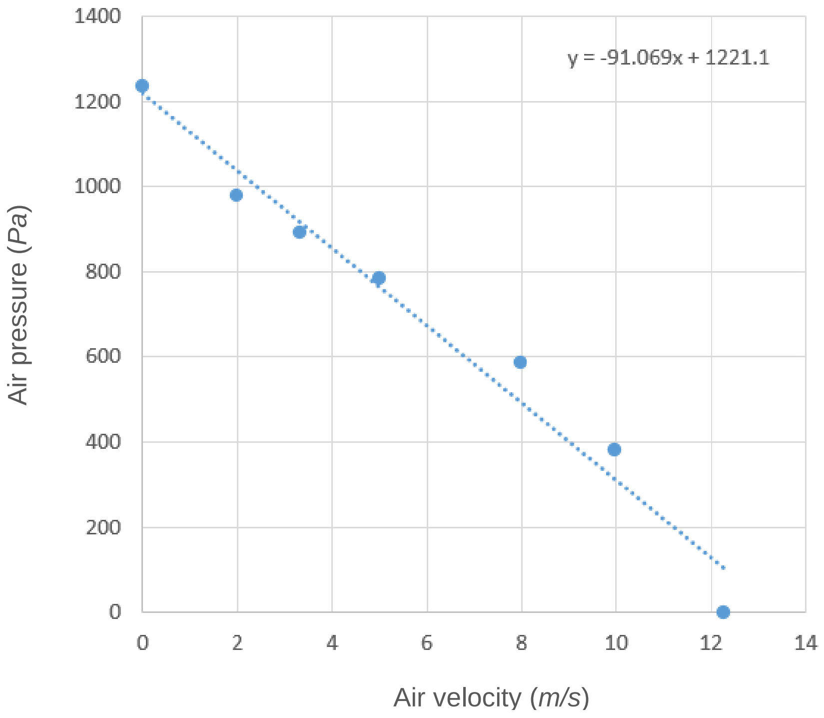

Figure 33 - Fan graph approximated in Excel

Figure 32 shows the transforming of measurements because Excel requires different ones than which are given by the manufacturer. Polynomial $y = -91.069x + 1221.1$ is given by Excel, shown in figure 33, and it has to be entered in Ansys.

4.1.4 Optimisation

The module geometry was optimized by changing the spacing between the cells, starting from 6 mm, which was observed in the work of other teams. We did not want to increase the height significantly to accommodate other parts of the car, so in vertical direction we settled on a maximum of 7 mm. Then, we varied the distance in the horizontal direction. We started from 6 mm, what turned out to be the maximum allowable to fit other components and decreased it by increments of 1 mm until the results began to deteriorate significantly to achieve the most compact package possible. Later, to obtain more relevant results, as the graphs for maximum temperature in a point were giving inconsistent results, a condition was added where the cells are divided into two groups: those near the outlet, where the highest cell temperature occurs, and all others. This was done to obtain a relevant result by considering the average temperature in these hottest cells instead of the maximum temperature at a point.

All the geometries look similar because the difference between them is only 1 mm, so I put only two pictures of 3 mm and 1 mm to see the difference in mesh.

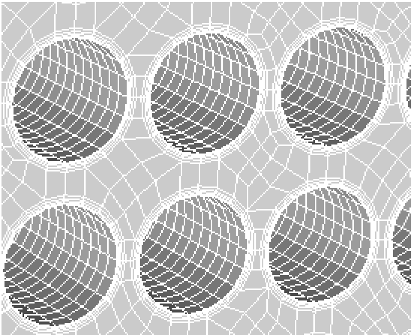

Figure 35 – Mesh for 3 mm

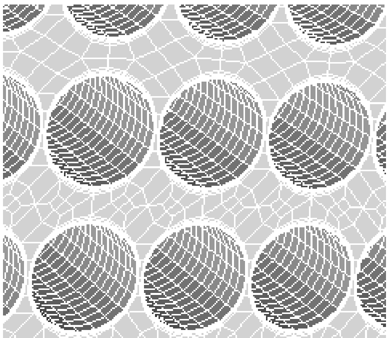

Figure 34 – Mesh for 1 mm

In the following figures the results are shown. Starting from 6 mm and finishing with 1 mm between the cells.

4.1.5 Results

The graph from which the results are taken is the graph of the average temperature of the last 10 cells closest to the exit because they are the hottest. In the figure 36 the graph for the 6 mm distance is showed and the temperature is around 333 K which is about 60 °C. It is in the acceptable range but barely so it is not the perfect solution because it does not leave space for error.

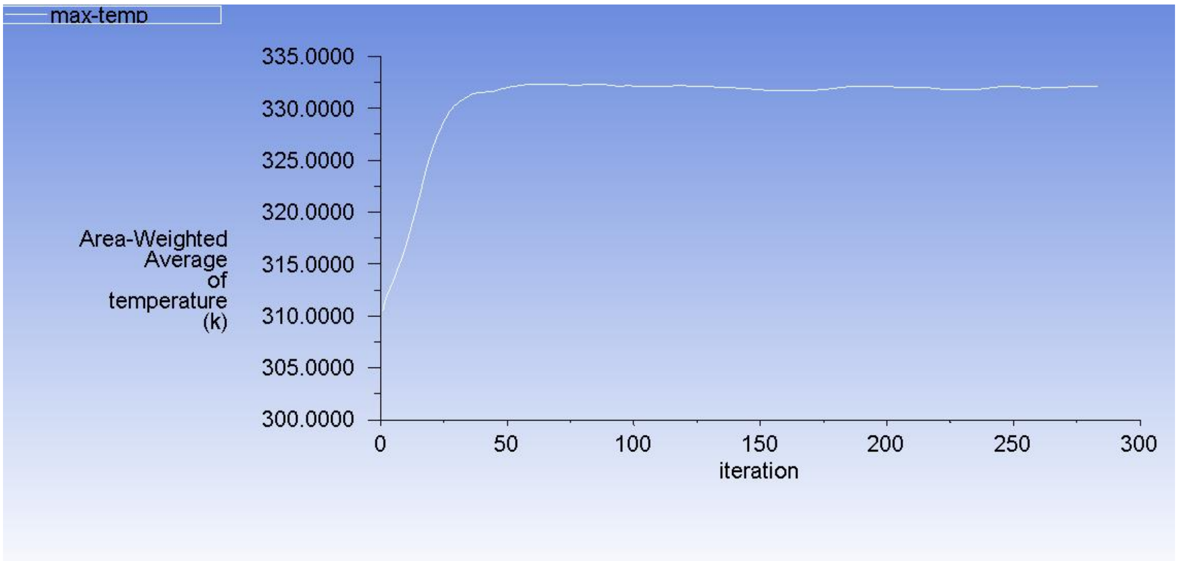

Figure 36 - Temperature for 6 mm

In the figure 37 the result of a simulation for 3 mm distance is shown and it is much better than the previous ones. The graph shows temperature of 327 K which is 54 °C and that is much more acceptable than in the case of 6 mm distance.

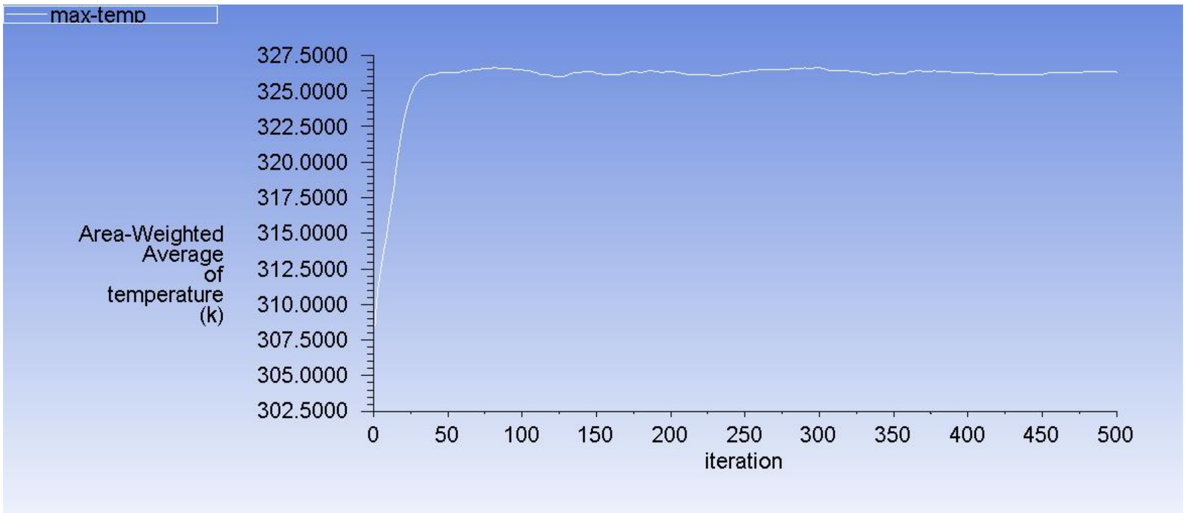

Figure 37 - Temperature graph for 3 mm

The simulations for 2 mm and 1 mm distance yielded similar results. The temperature graph was acceptable but heat throughout the pack was not distributed like it should have. It is shown in figure 40 that the heat is not distributed evenly in a way that the coldest is on the entrance and the hottest is on the exit but it generates hot spots on the entrance as well. For that reason, those cases could not be chosen with certainty that they are better than 3 mm case which is why ultimately 3 mm case was chosen. The bright red colours on the figure 40 show temperatures higher than 333 K what is not acceptable, but the figure shows maximum local temperature. What we need to have a reliable result is the average temperature on the whole face of the cell. For that reason, graphs like shown on figures 36 and 37 are what the results are taken from.

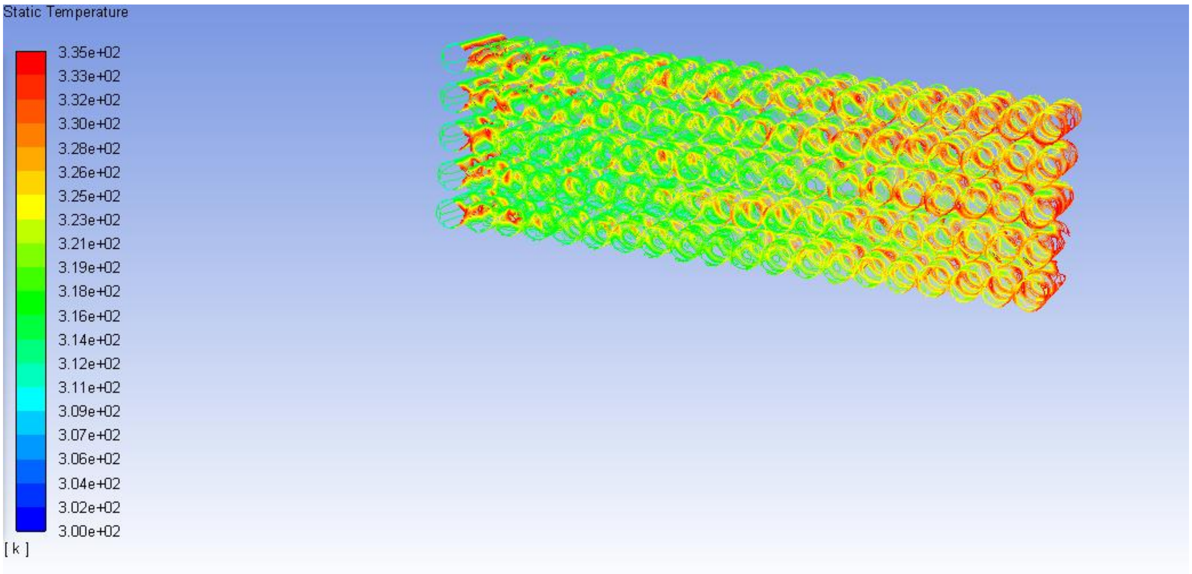

Figure 38 - Temperature for 1 mm

4.2 Final version

4.2.1 Model

For the final version a bit more complicated and realistic model is created. It has 95 cells in a module as mentioned before, air intake from the top and flaps to help direct the air into the cells. Simulation was done just to verify the results from the simpler version.

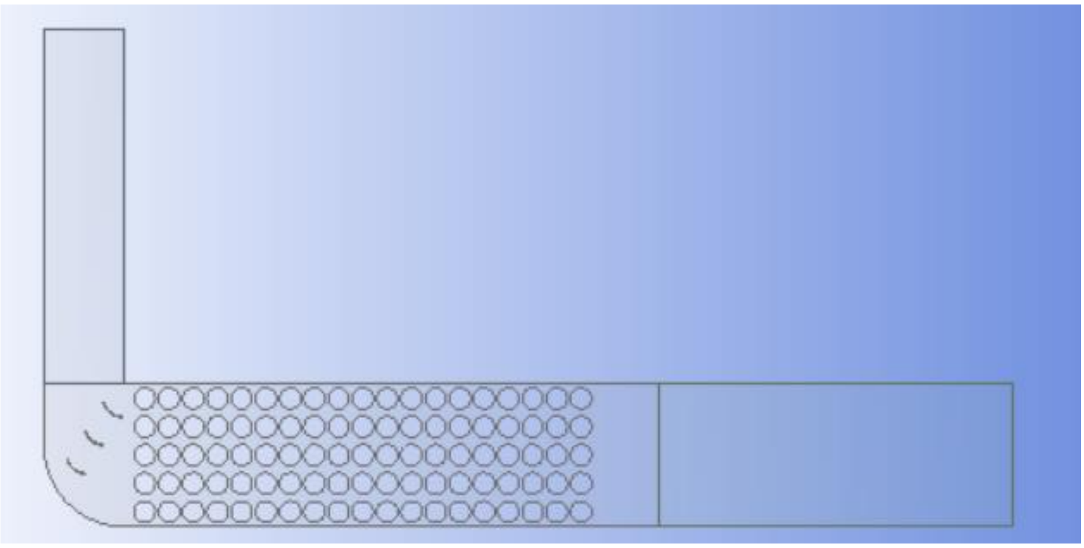

Figure 39 - Final model

4.2.2 Mesh

Mesh was optimized in the same way as the first version. Same mesh modification methods were used.

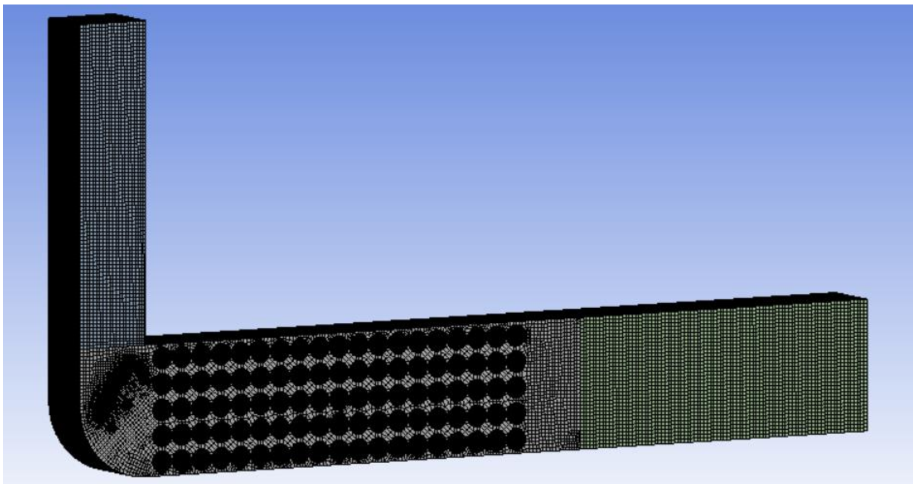

Figure 40 - Final version mesh

4.2.3 Results

Results proved the average temperature of around 327 K what is 54°C. The graph shows the average temperature of the two rows of cells furthest from the fan because they are the hottest ones, the same way as in the first version. Results are identical to the ones already done with simpler model so there is no need for extensive simulations.

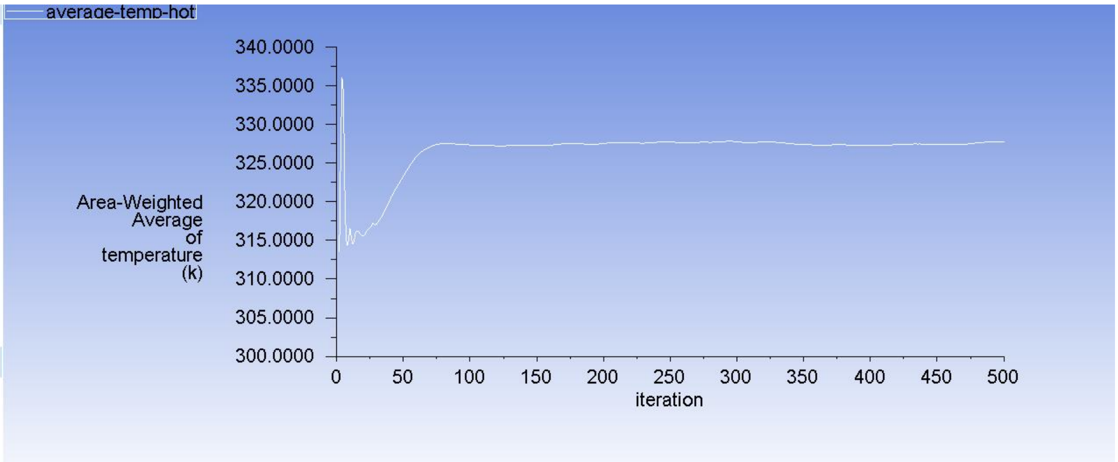

Figure 41 - Temperature graph

4.3 3D model

In the figures of this segment the 3D model of the battery pack made in SolidWorks is shown. First figure shows the interior of the whole pack, the position of the fans, cells, cell holders and the bus bars. In the second figure it can be seen that the pack is positioned behind and under the driver's seat resulting in the best possible weight distribution and allowing enough space for the other components of the car to be placed above and behind the pack.

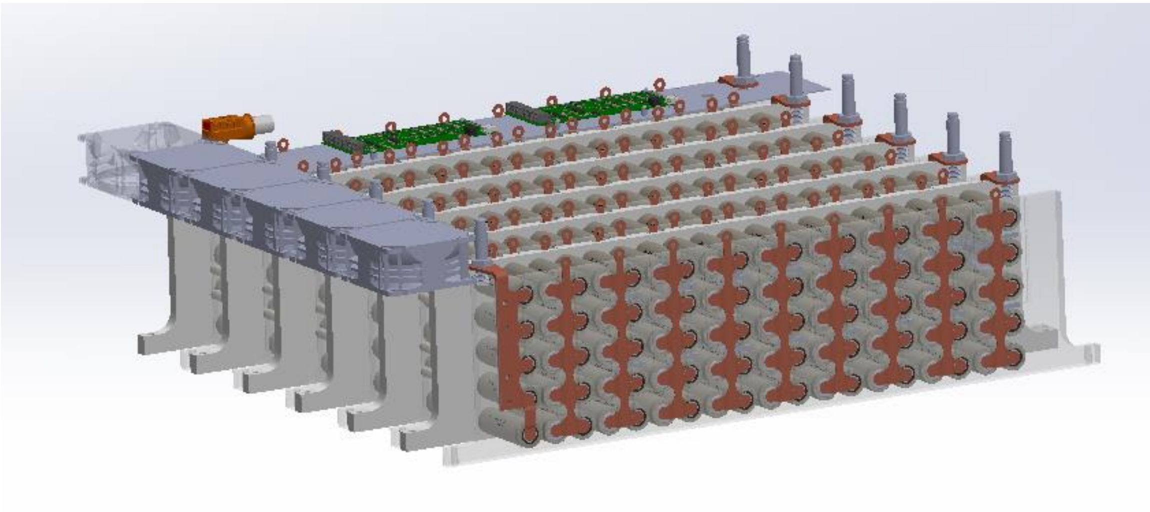

Figure 42 – Battery pack interior

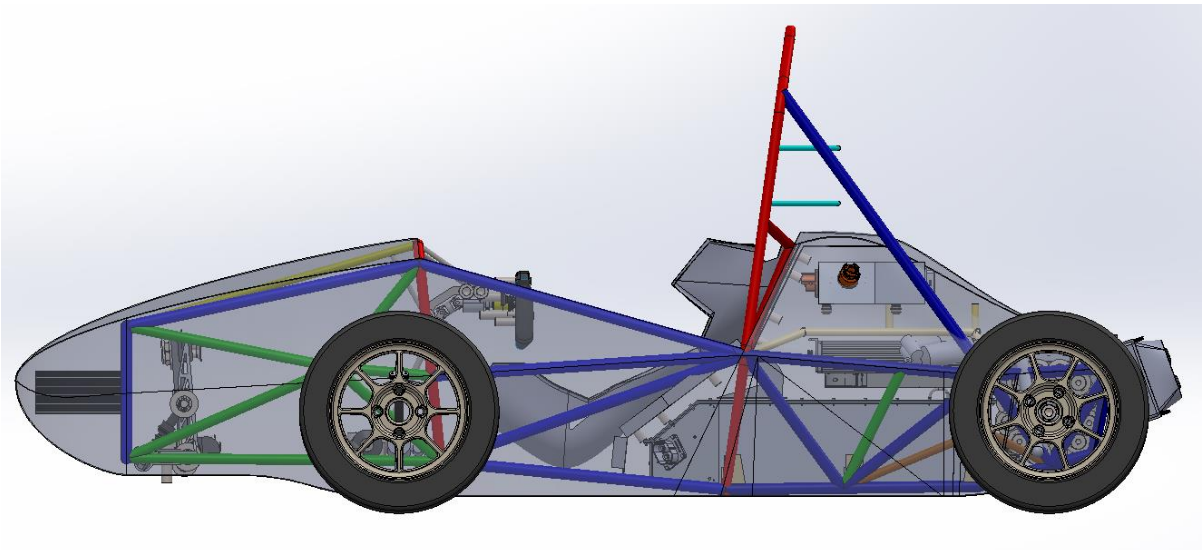

Figure 43 - Battery pack location

5 Conclusion

In this thesis, various cooling methods for the battery pack of a Formula Student car are explored. Through research and analysis, we examined liquid cooling, phase change materials (PCMs), and air cooling methods, ultimately selecting air cooling as the optimal solution for our application.

The primary objective was to optimize the air cooling system by adjusting the spacing between the battery cells. Starting with an initial distance of 6 mm and gradually decreasing it to 1 mm, a series of simulations were conducted to evaluate the thermal performance and efficiency of the cooling system. After simulations the configuration of 7 mm distance between the cells vertically and 3 mm distance horizontally is chosen as optimal.

Results indicate that reducing the spacing between the cells significantly improves the heat dissipation capability of the air cooling system. The closer cell arrangement facilitates better airflow distribution and enhances the convective heat transfer between the cells and the cooling air. As a result, the temperature of the battery pack was effectively maintained within safe operating limits, ensuring optimal performance and longevity of the battery cells.

Moreover, the air cooling system demonstrated several advantages, including lower weight and complexity compared to liquid cooling systems, and elimination of potential issues related to liquid leaks or maintenance. The simplicity of the air cooling design also allows for easier integration into the compact and lightweight structure of the Formula Student car.

In conclusion, the optimized air cooling method with reduced cell spacing proved to be an effective and efficient solution for managing the thermal behaviour of the battery pack in a Formula Student car. Future work may involve exploring advanced materials for improved thermal conductivity and further enhancing the cooling efficiency through innovative airflow management techniques.

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