Faculdade de Engenharia da Universidade do Porto



Cooling technics in automotive sector using new material - Numerical analysis

Luka Delić

Master thesis in mechanical engineering

Supervisor: Professor Abel Rouboa
Co-Supervisor: Professor Sandro Nižetić

19.6.2024

Abstract

With the rise in usage of the electric cars there is more focus on the maximizing performance of their key component-the battery package. Thermal management of the battery package is one of the most important tasks which insures vehicles performance, safety and longevity. There are various types of cooling battery packages such as air cooling, PCM, liquid cooling and refrigerant cooling. This thesis examines liquid cooling in detail and its main component – cooling channels which go around battery cells. This part is also known as cooling snake because of the shape. Main objective of this thesis is to compare materials from which the cooling snake is or can be made of. Today in the industry aluminum is number one material used for this because of its good conductivity of heat. The goal is to find replacement material – polymer which has good enough thermal properties but is cheaper and easier to manufacture. It is trend in the industry to replace metals with polymers because of the economic reasons. Heat dissipation channels are difficult to be replaced because polymers are naturally isolators and not conductors of heat. After finding the material with the desired specifications regarding not only thermal properties but the other critical properties also like chemical resistance, longevity, permeability, strength, the CFD simulation of the cooling snake gives insight on the difference between aluminum and polymer on the case of electric formula student car and determines the possibility of using the polymer as the cooling snake material.

Keywords: Liquid cooling, cooling snake, battery package, CFD, polymers

Abstrato

Com o aumento do uso de carros elétricos, há um foco maior em maximizar o desempenho de seu componente-chave – o pacote de baterias. A gestão térmica do pacote de baterias é uma das tarefas mais importantes para garantir o desempenho, a segurança e a longevidade dos veículos. Existem vários tipos de pacotes de baterias de resfriamento, como resfriamento a ar, PCM, resfriamento a líquido e resfriamento por refrigerante. Esta tese examina detalhadamente o resfriamento a líquido e seu componente principal – os canais de resfriamento que envolvem as células da bateria. Esta parte também é conhecida como "serpente de resfriamento" devido à sua forma. O objetivo principal desta tese é comparar os materiais dos quais a serpente de resfriamento é ou pode ser feita. Hoje, na indústria, o alumínio é o material número um usado para isso devido à sua boa condutividade térmica. O objetivo é encontrar um material substituto – um polímero que possua propriedades térmicas boas o suficiente, mas que seja mais barato e mais fácil de fabricar. É tendência na indústria substituir tudo o que é metálico por polímeros devido a razões econômicas, mas os canais de dissipação de calor ainda não foram substituídos porque os polímeros são naturalmente isolantes e não condutores de calor. Após encontrar o material com as especificações desejadas, considerando não apenas as propriedades térmicas, mas também outras propriedades críticas, como resistência química, longevidade, permeabilidade e resistência, a simulação CFD da serpente de resfriamento fornece uma visão sobre a diferença entre o alumínio e o polímero no caso do carro elétrico de fórmula estudantil e determina a possibilidade de usar o polímero como material para a serpente de resfriamento.

Index

List of figures..... viii

Chapter I..... 11

Introduction 11

State of the art 14

Chapter II..... 16

Batteries 16

Liquid cooling system 20

Theory behind heat transfer 24

Materials 28

Chapter III 36

CFD Simulation 36

Physical model 37

Mesh 41

Set-Up 43

Simulation results..... 46

Conclusion 49

List of figures

Figure 1 Graph that shows dependency range / temperature [2] 12

Figure 2 Battery package from the EV [6] 19

Figure 3 scheme of liquid cooling for battery package [3] 20

Figure 4 Low temperature radiator [8] 21

Figure 5 Colling plate [9] 22

Figure 6 Aluminum cooling snake [10] 23

Figure 7 Conduction from fluid A to Fluid B through solid wall [11] 25

Figure 8 Temperature gradient and fluid speed in border layer with heat transfer from the wall to the flowing fluid (up) and from the flowing fluid to the wall (down) [11] 27

Figure 9 Multi-channel tubes [16] 31

Figure 10 Performance debit versus aluminum (k=180 W/m K) and stainless steel (k=16 W/m K) [20] 32

Figure 11 Permeation in polymers 33

Figure 12 Model of the battery cells 38

Figure 13 Isometric view of the model of the cooling snake 39

Figure 14 Model of the cooling snake 39

Figure 15 Detail of the canal of the cooling snake 40

Figure 16 Model of the fluid (water) 40

Figure 17 Complete model of the battery with cooling snake 41

Figure 18 Meshed model 42

Figure 19 Detail of the mesh on cooling snake and the water 42

Figure 20 Faces representing interface between the snake and the battery cells 44

Figure 21 Inlet (blue) and outlet (red) 45

Figure 22 Temperature on the outlet.....46

Figure 23 Temperature on the surface of the aluminum cooling snake 47

Figure 24 Temperature on the outlet.....47

Figure 25 Temperature on the surface of the polymer cooling snake 48

List of Tables

Table 1 Physical properties of aluminum [12] 28

Table 2 Thermal properties of aluminum [12] 29

Table 3 Electrical properties of aluminum [12] **Pogreška! Knjižna oznaka nije definirana.**

Table 4 Mechanical properties of aluminum [12] 30

Table 5 Designation of the aluminum alloys [13] 30

Table 6 List of suitable polymer composites [20] 35

Table 7 Characteristics of the battery cell 37

Table 8 Water datasheet from Ansys 43

Table 9 Aluminum datasheet from Ansys 43

Table 10 Batteries datasheet 43

Table 11 Polymer (PPS) datasheet 44

Chapter I

Introduction

Internal resistance, chemical reactions, and inefficiencies in the battery's operation are the primary reasons why batteries produce heat during charging and discharging cycles. Batteries contain materials that conduct electricity, such as electrolytes and electrodes. However, these materials are not perfect conductors, they possess a certain amount of resistance to the flow of electric current. When the current flows through the battery, it encounters this resistance. According to Ohm's Law

$$U = I \times R \tag{1.1}$$

where U is voltage, I is current, and R is resistance

when current flows through a resistor, it generates heat.

$$P = I^2 \times R\ R \tag{1.2}$$

where P is power

This resistance within the battery causes some of the electrical energy to be converted into heat energy, leading to the battery heating up during use. Batteries operate based on chemical reactions that occur between the materials inside them.[1] During discharge, chemical reactions take place at the electrodes, where ions move from one electrode to another through the electrolyte. These chemical reactions are typically exothermic, meaning they release energy in the form of heat. For example, in a lithium-ion battery, during discharge, lithium ions move from the negative electrode (anode) to the positive electrode (cathode) through the electrolyte, releasing energy in the

process. The heat generated by these chemical reactions contributes to the overall temperature increase of the battery.

Because of this cooling of the batteries is required and offers several advantages.

Firstly, it optimizes the performance and efficiency of battery packs by regulating their operating temperatures within an ideal range. This controlled thermal environment ensures that the battery cells can consistently deliver their rated power and capacity, by mitigating the adverse effects of heat buildup, cooling systems prevent performance degradation, thereby maximizing the overall efficiency of the battery system. This consistency is critical for applications such as electric vehicles, where performance variability can impact driving range, acceleration, and overall user experience.

The optimum temperature of EV batteries is typically around 21 C⁰ However, efficiency can significantly drop if the battery gets too hot or too cold. A study conducted by Geotab [2] analyzed 5.2 million trips taken by 4,200 EVs and found that at temperatures of 0 C⁰ and 40 C⁰, an EV can drop to around 80% of its rated driving range. While at more extreme temperatures such as -20 C⁰, an EV can only achieve 49% of its rated range. This means that on a particularly cold day in countries like Canada, an electric vehicle that is rated to do 402 km would only be capable of 197 km on average. Consequently, EV cooling circuits require both heating and cooling elements to warm the battery up when it is too cold and cool it down when it is too hot.

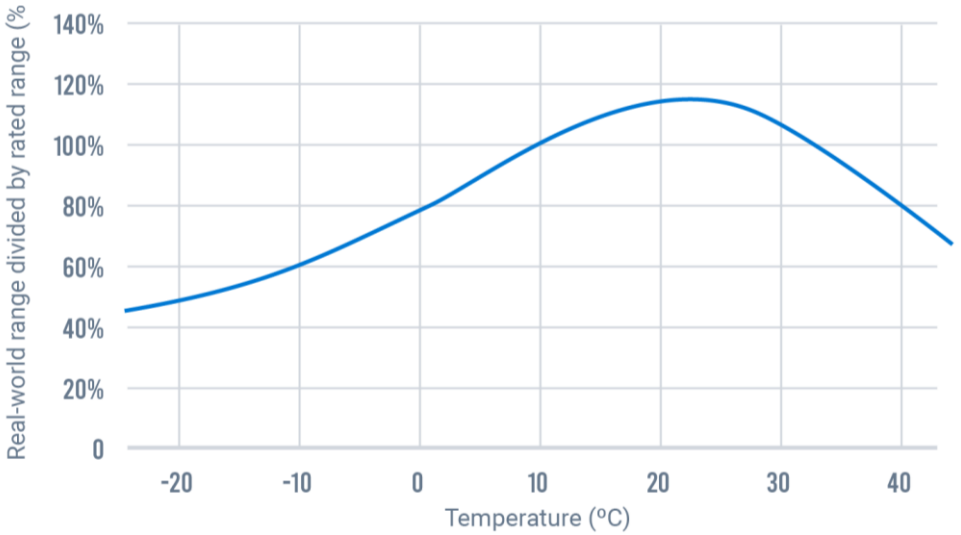


Figure 1 Graph that shows dependency range / temperature [2]

Secondly, cooling systems contribute to the extended lifespan of battery packs by minimizing thermal stress. Lithium-ion batteries are sensitive to temperature variations. Excessive heat can accelerate degradation mechanisms within the battery cells, leading to reduced capacity and shortened lifespan. By actively dissipating heat during charging, discharging, and idle periods, cooling systems eliminate these detrimental effects, thus preserving the battery's long-term health and functionality.

Thirdly, the implementation of cooling systems facilitates faster charging rates without compromising safety or battery integrity. During rapid charging, heat generation within the battery cells can increase significantly, leading to elevated temperatures and potential safety hazards. Cooling systems allow faster charging without exceeding safe temperature limits. This capability is particularly crucial in electric vehicles, where efficient charging infrastructure and minimal charging time are biggest considerations for consumers.

Furthermore, cooling systems enhance overall safety by mitigating the risk of thermal runaway events. Thermal runaway occurs when a battery cell undergoes uncontrolled exothermic reactions, leading to rapid temperature escalation and potentially catastrophic failure.

Cooling of the battery is of great importance for the safety and performance so liquid cooling system will be more examined. In this thesis main objective is to compare different materials such as aluminum and polymers and their ability to be used as cooling snake (heat pipes) through which coolant flows in the battery package. It is important to compare various properties of the selected materials such as weight, strength, resistance to high temperatures, resistance to different coolants, longevity, simplicity and cost of production and of course the heat dissipating properties.

State of the art

EV technology is relatively new so every manufacturer has its own way of engineering systems and thus there are few different ways to keep the battery package cool.

Air cooling relies on the circulation of air to remove heat from the battery pack. Heat transfer occurs through convection, where the warmer battery surfaces transfer heat to the surrounding air, which then rises and is replaced by cooler air. Fans or natural convection can enhance this process. A lot of EV's use this method [3][4][5].

Liquid cooling systems use a fluid (usually water or a water-glycol mixture) to absorb heat from the battery cells. The warm coolant flows through channels or pipes within the battery pack, absorbing heat through conduction. It then carries this heat away to a heat exchanger where it is cooled before returning to the battery pack. The Chevrolet Bolt EV utilizes a liquid cooling system for its battery pack [3][4][5].

Phase Change Material (PCM) Cooling utilizes materials that change phase (from solid to liquid or vice versa) at specific temperatures. When the battery generates heat, the PCM absorbs this heat as it changes phase, effectively storing the thermal energy. As the surrounding temperature decreases, the PCM solidifies again, releasing the stored heat. The Tesla Model S incorporates a phase change material in its battery pack for passive cooling [4][5].

Thermoelectric coolers exploit the Peltier effect, where a temperature difference is created when an electric current flows through a junction of two dissimilar conductors. This temperature difference causes heat to transfer from one side of the junction (the hot side) to the other (the cold side), providing cooling on one end of the device while heating the other. The Porsche Taycan utilizes thermoelectric coolers [4].

Direct refrigerant cooling systems use a refrigerant fluid circulated through the battery pack. The refrigerant absorbs heat from the battery cells as it evaporates, becoming a low-pressure gas. This gas is then compressed, raising its temperature, before it condenses back into a liquid in a heat exchanger where the heat is released. The liquid refrigerant then returns to the battery pack to repeat the cycle. Audi e-tron features a direct refrigerant cooling system [3].

In indirect refrigerant cooling, a separate loop of refrigerant is used to cool a secondary coolant, such as water or glycol, which is circulated through the battery pack. The refrigerant absorbs heat from the secondary coolant through a heat exchanger, then goes through the compression-condensation cycle as in direct refrigerant cooling. The BMW i3 employs an indirect refrigerant cooling system [3].

Phase change cooling utilizes materials that change phase to absorb heat. However, instead of storing heat as latent heat during a phase change, phase change cooling systems actively transport the phase change material away from the battery cells to release the stored heat elsewhere. The Nissan Leaf uses a phase change cooling system [4].

Heat pipes are passive heat transfer devices consisting of a sealed tube containing a working fluid (often water). When one end of the heat pipe is heated, the working fluid evaporates, carrying heat away as a vapor to the cooler end of the pipe where it condenses back into a liquid, releasing the heat. The condensed liquid then returns to the heated end via capillary action, completing the cycle. Heat pipes can efficiently transfer heat over long distances with minimal temperature gradients. The Jaguar I-PACE utilizes heat pipes integrated into the battery pack.

Chapter I I

Batteries

The battery is one of the most crucial and also most expensive components of any electric vehicle. Not only do factors such as vehicle performance, including range and weight, depend on it, but also price, charging speed, and the vehicle's environmental impact. The battery is a device that converts chemical energy into electrical energy. Battery cells consist of an anode, cathode, and electrolyte. The anode reacts with the electrolyte and releases electrons, while simultaneously, a reaction occurs at the cathode, allowing the acceptance of electrons. As a result, an electrical potential, or voltage, is created, and when the anode and cathode are connected by a conductor, electrons, or electric current flow through it. Batteries are constructed from a large number of battery cells that are connected in battery modules, ultimately forming a battery pack. A single pack can consist of thousands of cells, which can be cylindrical, prismatic, or pouch shaped. For the automotive industry, the most critical battery parameter is energy density, which refers to energy per unit of mass or volume [Wh/kg], [Wh/l]. The development of new batteries aims to achieve higher energy density in the battery pack, with the goal of obtaining batteries with higher capacity and less weight. The range of an electric vehicle directly depends on the battery's capacity. Battery capacity is a measure of how much energy can be drawn from the battery under specific conditions. It is expressed in ampere-hours [Ah] or, more commonly for electric vehicle batteries, watt-hours [Wh]. Simplified, this means that for 1 hour of operation of a 100 W bulb, a battery with a capacity of 100 Wh is required. Battery capacity significantly depends on the ambient temperature; thus, if it is too cold or too hot, the expected vehicle autonomy cannot be achieved. With technological advancements, battery capacity, and thus the range of electric vehicles, continue to increase.

Type of batteries

There are many types of batteries based on their chemical composition, each with its own characteristics, including advantages and disadvantages. The first batteries used in vehicles were lead-acid batteries, and although they are inexpensive, they have fallen out of use due to their weight and environmental impact. They were succeeded by nickel-based batteries, namely nickel-cadmium and nickel-metal hydride. Currently, lithium-based batteries are considered the pinnacle of technology.

Lead-acid batteries (Pb-PbO2):
These are the oldest type of rechargeable batteries, often used in vehicles with internal combustion engines for ignition. They have very low energy density, meaning a battery with the required capacity for an electric vehicle with an acceptable range would be excessively heavy. Another issue is that lead is toxic to humans, and improper disposal can lead to environmental pollution.

Nickel-cadmium batteries (Ni-Cd):
These batteries have higher energy density, but they suffer from memory effect, poor charging and discharging efficiency, poor performance in cold weather, and a short lifespan, which hinder their use. Additionally, cadmium is a very expensive and toxic element.
Nickel-Metal Hydride (Ni-MH):

Similar to nickel-cadmium batteries, but instead of cadmium, a metal that stores hydrogen is used as the negative electrode. They have self-discharge during non-use of up to 20% per month. They have been used in cars like the Toyota Prius and Toyota RAV4 EV.

Lithium batteries:
Lithium is the most electronegative element and is therefore used. Lithium batteries have high energy density, meaning battery packs can be lighter, capable of fast charging, have very low self-discharge during non-use, recyclable, and environmentally friendly. These characteristics have led to

their predominant use in the production of electric vehicles. Lithium batteries are divided into Lithium nickel manganese cobalt (NMC), Lithium nickel cobalt aluminum oxide (NCA), Lithium iron phosphate (LFP), and others not used in electric vehicles. NMC is the most used; NCA has slightly higher specific energy than NMC but is potentially more hazardous, used only by Tesla manufactured by Panasonic. LFP has a longer lifespan, meaning they can withstand more charging cycles (up to 5000) and are safer at increased temperatures and mechanical damage, but they have slightly lower energy density. Tesla is transitioning more than 50% of its vehicles to this technology.

In electric vehicles (EVs), the most used battery types are typically pouch cells, prismatic cells, and cylindrical cells. Each type has its advantages and is chosen based on factors such as energy density, packaging efficiency, thermal management, and manufacturing considerations.

Pouch cells are frequently used in electric vehicles due to their flexibility in design and packaging. They consist of layers of electrode and separator materials enclosed in a flexible, flat pouch. Pouch cells offer advantages in terms of weight reduction, space efficiency, and thermal management. They are commonly found in modern electric vehicles from various manufacturers.

Prismatic cells have a rectangular or square shape with a flat profile. They are favored for their ease of stacking and packaging efficiency, making them suitable for applications where space optimization is crucial, such as in electric vehicles. Prismatic cells are known for their stable performance and are widely used by many EV manufacturers.

Cylindrical cells, such as 18650 and 21700 cells, are also commonly used in electric vehicles, especially in early-generation EV models. These cells have a long history of use in consumer electronics and are known for their reliability, robustness, and ease of manufacturing. While cylindrical cells may be slightly less space-efficient compared to pouch and prismatic cells, they offer advantages in terms of cost-effectiveness and proven performance.

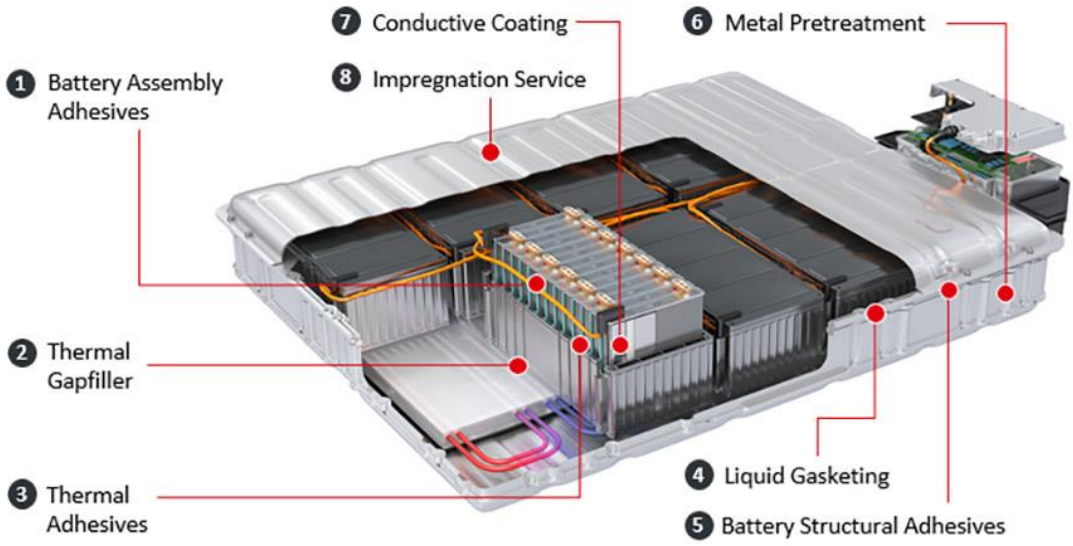


Figure 2 Battery package from the EV [6]

For the purpose of this dissertation cylindrical cells will be used to create battery package for the EV.

Liquid cooling system

As already mentioned, liquid cooling system uses liquid (for example water) running through pipes which takes heat from the heat producing element and transports that thermal energy to the heat exchanger where it is dissipated to the environment so the liquid is cooled and ready to take more heat [3]. The system is closed which means that the fluid in the pipes does not mix with any other fluid, only way of transferring thermal energy is through convection on pipes and heat exchanger. The cooling liquid travels through pipes and comes into contact with the battery via an intermediary, such as fins or heat sinks. Alternatively, for cylindrical batteries, a ring-jacketed structure can be employed. Since there are no insulation requirements and no restrictions on flow rate, a liquid with high thermal conductivity can be chosen, resulting in efficient heat exchange. Ensuring tightness of the pipeline is essential in indirect contact systems to prevent leakage and short circuits. Liquid cooling system is simple and is consisted of only few parts: coolant pump, heat exchanger, connecting pipes, cooling plate or cooling snake.

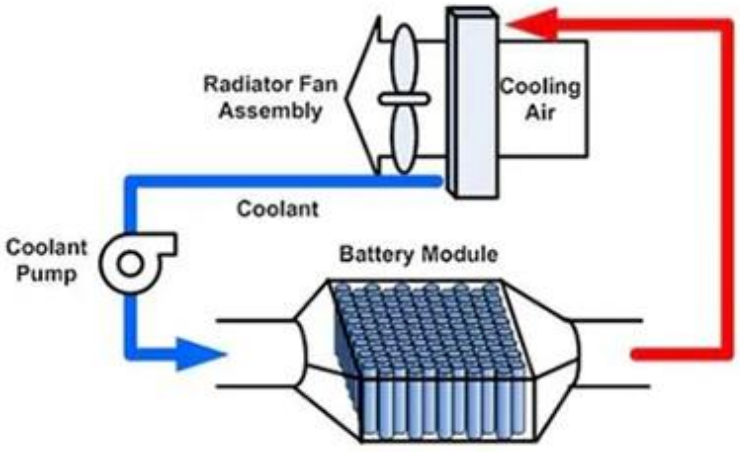


Figure 3 scheme of liquid cooling for battery package [3]

Pumps

Electric pumps are mostly used to push the coolant through the circuit instead of mechanical ones because they can be mounted anywhere convenient and can be turned on only when necessary. For example if it is cold temperature outside there is no need for the great heat transfer so the pump does not need to work all the time and thus the energy is saved.

Centrifugal pumps used in EV battery cooling systems may have flow rates ranging from 5 to 20 liters per minute (L/min) or more, depending on the size and cooling requirements of the battery pack.

Typical pressure ranges for automotive centrifugal pumps may be between 0.5 to 2 meters of water column or more.

Centrifugal pumps for automotive applications are typically designed to operate within standard vehicle electrical systems, such as 12 volts (V) or 48 volts (V), to ensure compatibility with the vehicle's power supply.

Centrifugal pumps used in EV battery cooling systems should be capable of operating within the temperature range encountered in automotive applications, typically between -40°C to 120°C

Centrifugal pumps for EV battery cooling systems are typically compact and lightweight to minimize space requirements and vehicle weight. These pumps may have dimensions on the order of tens of centimeters and weigh a few kilograms or less [7].

Heat exchanger

Heat exchanger in electric vehicles is often just a low temperature radiator from which stream of air by convection picks up the thermal energy and dissipates it to the environment.

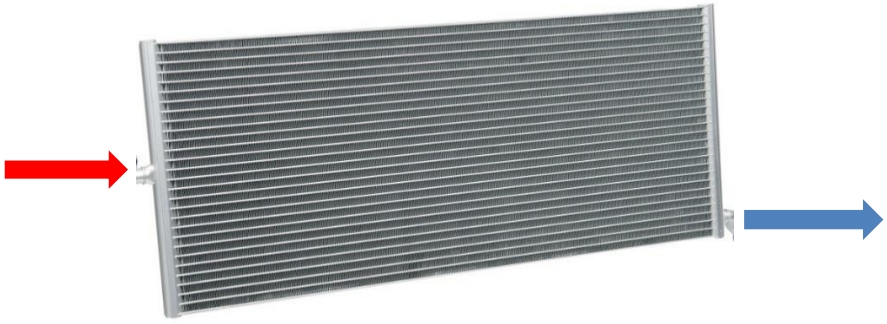


Figure 4 Low temperature radiator [8]

Cooling plates and cooling snakes

Cooling plates are flat structures or plates with tubes running through them through which a cooling fluid flows and dissipates heat. Batteries are put onto plates and thermal energy is transferred to them and the fluid inside them.



Figure 5 Colling plate [9]

Cooling tubes, or heat exchange tubes in batteries (also known as cooling snakes because of their shape) are conduits through which a cooling fluid flows to absorb heat from a heat source.

In liquid cooling systems for cooling channels inside the battery package of electric vehicles, several materials with high thermal conductivity are commonly used.

Aluminum is a lightweight and corrosion-resistant material commonly used for manufacturing cooling plates and channels within battery packs. It offers good thermal conductivity, facilitating efficient heat transfer from the battery cells to the cooling fluid.



Figure 6 Aluminum cooling snake [10]

Copper is another material with excellent thermal conductivity, making it suitable for use in cooling systems. It is often used in heat exchangers, tubing, and connectors within liquid cooling systems to enhance heat dissipation from the battery cells.

Stainless steel is valued for its corrosion resistance and durability. It is used in components such as tubing and fittings within liquid cooling systems to ensure longevity and reliability in harsh operating environments.
Rubber or silicone seals and gaskets are essential for ensuring leak-proof connections and maintaining the integrity of liquid cooling systems. These flexible materials provide effective sealing to prevent coolant leakage [12].

In some high-performance applications, ceramic materials may be used for manufacturing components like heat exchangers or coolant passages within battery packs. Ceramic materials offer excellent thermal stability and resistance to corrosion and erosion.

Polymer materials are generally not used as the primary cooling conduits or "snakes" within liquid cooling systems for battery packs in electric vehicles. However, polymer materials may still play a role in supporting or insulating these cooling conduits within the battery pack assembly. For example, they might be used as protective coatings on metal cooling pipes or as insulation around coolant lines to minimize heat transfer to the surrounding environment. High-performance plastics or composite materials may be used for manufacturing components like coolant reservoirs, headers, and manifolds within liquid cooling systems. These materials offer lightweight and corrosion-resistant alternatives to metal components [12].

Purpose of this thesis is to investigate possibility of using polymer materials as primary cooling conduits instead of metal especially aluminum, make a comparison between them and to determine biggest limiting factors for the replacement.

Theory behind heat transfer

The heat transfer from the battery to the environment is consisted of different mechanisms of heat transfer such as convection and conduction. To have the best possible results it is important to clarify what exactly is happening in the process so the problem will be divided to a several of smaller problems.

First problem is that the battery cells don’t give continuous heat flow. The battery produces heat only when it is under the heavy load when it is discharging. When the vehicle is not accelerating there is no heat flow. This is problem because the heat flow must be averaged so that calculations are simpler to make. It is needed to exchange peaks of heat flow (maximum discharge) and periods of not producing any heat flow (no discharge) with averaged continuous heat flow. For example, the electric formula student car will be used.

Conduction

Now when continuous heat flow from batteries is determined we can use it to calculate conduction through the wall of cooling snake. Conduction is one of the three primary methods of heat transfer, alongside convection and radiation. In conduction, heat energy is transferred through a material or between materials that are in direct contact with each other.

The rate of heat conduction depends on several factors, including the thermal conductivity of the material, the temperature gradient (difference in temperature) across the material, and the thickness of the material. Materials with high thermal conductivity, such as metals, are efficient conductors of heat and transfer heat more quickly than materials with lower thermal conductivity, such as wood or polymers.

Battery cells are in direct contact with the cooling snake so the conduction is happening between them, heat is transferred from the cells to the cooling snake.

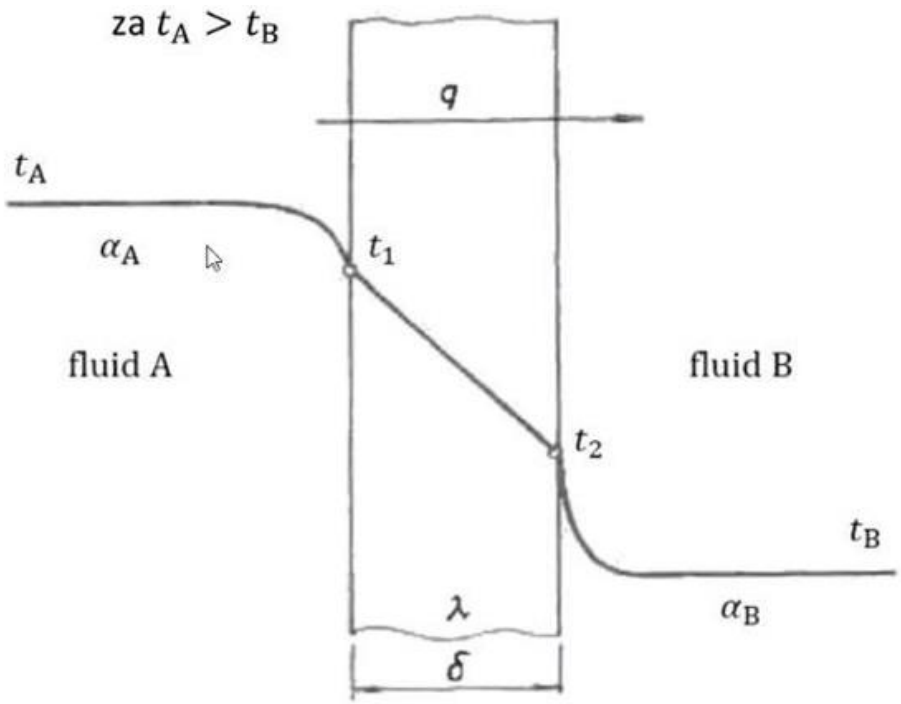


Figure 7 Conduction from fluid A to Fluid B through solid wall [11]

$$\dot{q} = -\frac{t_1 - t_A}{\frac{1}{\alpha_A}} = \alpha_A(t_A - t_1) \tag{2.1}$$

$$\dot{q} = -\frac{t_2 - t_1}{\frac{\delta}{\lambda}} \tag{2.2}$$

$$\dot{q} = -\frac{t_B - t_2}{\frac{1}{\alpha_B}} = \alpha_B(t_2 - t_B) \tag{2.3}$$

$$\dot{q} = -\frac{t_B - t_A}{\frac{1}{\alpha_A} + \frac{\delta}{\lambda} + \frac{1}{\alpha_B}} = -k(t_B - t_A) = k\Delta t \tag{2.4}$$

Where;

t_1 is temperature on the wall on the side of fluid A [K]

t_2 is temperature on the wall on the side of fluid A [K]

t_A is temperature of the fluid A away from the wall [K]

t_B is temperature of the fluid B away from the wall [K]

$\dot{q}$ is heat transfer rate [W]

k is heat transfer coefficient [W/m^2K]

Convection

Convection is one of the primary methods of heat transfer. It involves the transfer of heat energy through the movement of fluids (liquids or gases) between the fluid and solid body. It can be caused by density differences within the fluid because of temperature differences (natural convection) or by forced movement of fluid using the pumps or the fans (forced convection).[11]

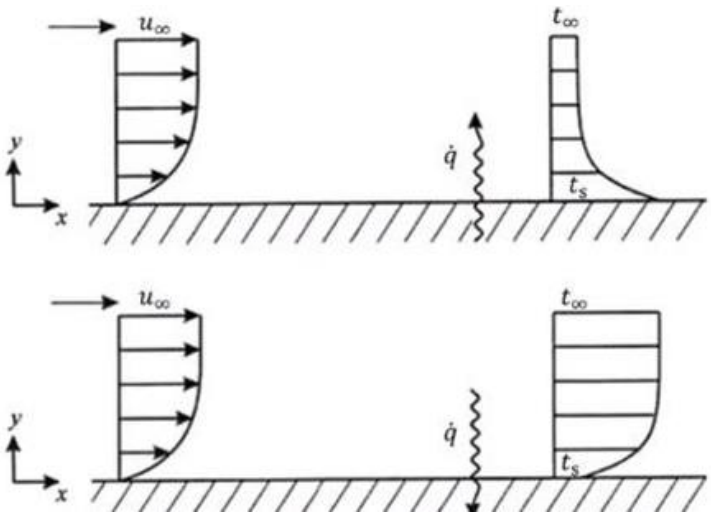


Figure 8 Temperature gradient and fluid speed in border layer with heat transfer from the wall to the flowing fluid (up) and from the flowing fluid to the wall (down) [11]

It is described by Newtons equation

$$\dot{Q} = \alpha A(t_s - t_\infty) \tag{2.5}$$

$$\dot{q} = \frac{\dot{Q}}{A} = \alpha(t_s - t_\infty) \tag{2.6}$$

Where;

t_s is temperature of the wall

t_∞ temperature of the fluid away from the wall $[K]$

A is surface of the wall $[m^2]$

$\dot{q}$ is heat transfer rate $[W]$

α is is heat transfer coefficient $[W/m^2K]$

Coefficient α is the most important to determine because it determines the heat flow from fluid to wall or vice versa. It is a consequence of the different properties such as fluid's viscosity, speed, regime of flow (laminar, turbulent), density, cp specific heat capacity… It is determined by using dimensionless quantities Reynold's, Prandtl's and Nusselt's number [11]. Their formulas depend on the shape of the wall on which the fluid is flowing.

Materials

In this chapter materials that are going to be used in simulations will be closer examined. As the main topic of the thesis says, main objective is to compare aluminum and different polymers for the purpose of the making cooling snake. Most important thing from the engineering perspective is to analyze their thermodynamical properties so the focus of the simulations so that will be the focus of the simulations. Other physical properties of the chosen materials are also going to be examined if they somehow change the performance of the cooling or performance of the entire cooling system.

Aluminum

Aluminum mechanical properties will be closer looked at first because that is the material which is currently most used in this application. Also, to find the good replacement for it among the polymers, it's best that it's advantages and flaws are well known.
All listed properties are for technical pure aluminum while aluminum alloys or heat-treated aluminum can have significantly different properties.

Table 1 Physical properties of aluminum [12]

Physical Properties	
Density	2.6989 g/cm^3

Table 2 Thermal properties of aluminum [12]

Thermal Properties	
Heat of Fusion	386.9 J/g
Heat of Vaporization	9462 J/g
CTE, linear Temperature 20.0 - 100 °C	24.0 µm/m-°C
Temperature 20.0 - 300 °C	25.5 µm/m-°C
Temperature 20.0 - 500 °C	27.4 µm/m-°C
Specific Heat Capacity	0.900 J/g-°C
Thermal Conductivity	210 W/m-K
Melting Point	660.37 °C
Boiling Point	2519 °C

Table 3 Mechanical properties of aluminum [12]

Mechanical Properties	
Hardness, Vickers	15
Modulus of Elasticity	68.0 GPa
Poissons Ratio	0.36
Shear Modulus	25.0 GPa

Aluminum is most commonly alloyed with copper, zinc, magnesium, silicon, manganese and lithium. Small additions of chromium, titanium, zirconium, lead, bismuth and nickel are also made and iron is invariably present in small quantities.[13] Aluminum alloys are used for making cooling snakes.

Table 4 Designation of the aluminum alloys [13]

Alloying Element	Wrought
None (99%+ Aluminum)	1 xxx
Copper	2 xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5 xxx
Magnesium + Silicon	6 xxx
Zinc	7 xxx
Lithium	8 xxx

Because of its good weldability and formability and very good corrosion resistance aluminum 3003-H16 is often used for making heat exchangers. H16 means that that aluminum was work hardened to three-quarter hard–degree of working [13].

Process of producing cooling snake consists of several steps. First, multi-channel tubes, are typically made using a process called porthole die extrusion and after are worked to the shape of snake. Endings are welded together with the inlet and outlet [14][15].

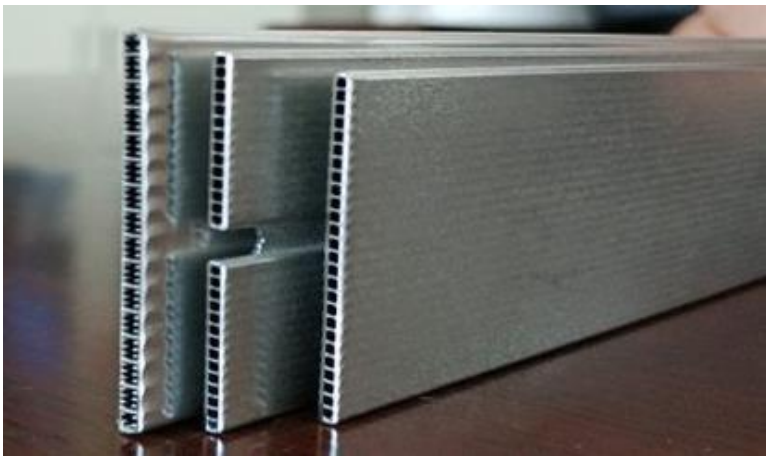


Figure 9 Multi-channel tubes [16]

Polymers

A polymer is a substance or material consisting of very large molecules, or macromolecules, composed of many repeating subunits, known as monomers. Polymers can be both naturally occurring and synthetic. Natural polymers include materials such as hemp, wool, silk, natural rubber, cellulose. Synthetic polymers include plastics such as polyethylene, polypropylene, and polystyrene. Main reason why to replace aluminum with polymers is the ease of production, for example, the manufacturing time for polymer composite heat exchangers is expected to be reduced compared to typical metallic heat exchangers. Total materials costs and overall manufacturing costs could be reduced. Manufacturing techniques such as 3D printing should be explored as a way to increase the design space.

Polymers generally have low thermal conductivity, which is a main factor limiting their expanded use in new applications. This means they don't conduct heat well, which can limit their effectiveness as heat pipes. The thermal conductivity of polymers can be improved effectively by adding high heat absorbing fillers such as ceramics, metals, carbon fillers, and metallic oxides [19][20]. Whereas unfilled thermoplastics have a thermal conductivity of around 0.2 W/m K, most thermally conductive plastic compounds typically have 10 to 50 times higher conductivity (1-10 W/m K) [19]. These examples illustrate that while thermoplastic polymers inherently have low thermal conductivity, their thermal conductivity can be significantly improved through various strategies, such as the addition of high thermal conductivity fillers [20].

However, it can be argued that metals high thermal conductivity cannot be effectively utilized if they conduct heat to the surface of a product faster than flow convection can remove heat from the surface which means that heat transfer in many applications is convection-limited (design-dependent), not conduction-limited (material-dependent) [19]. A typical heat exchanger design and a realistic thickness for the composite layer were assumed. Debit may be recoverable through design changes that cannot be afforded by a metal construction. The thermal conductivity of the aluminum can be compensated by using thinner layers of polymers [20].

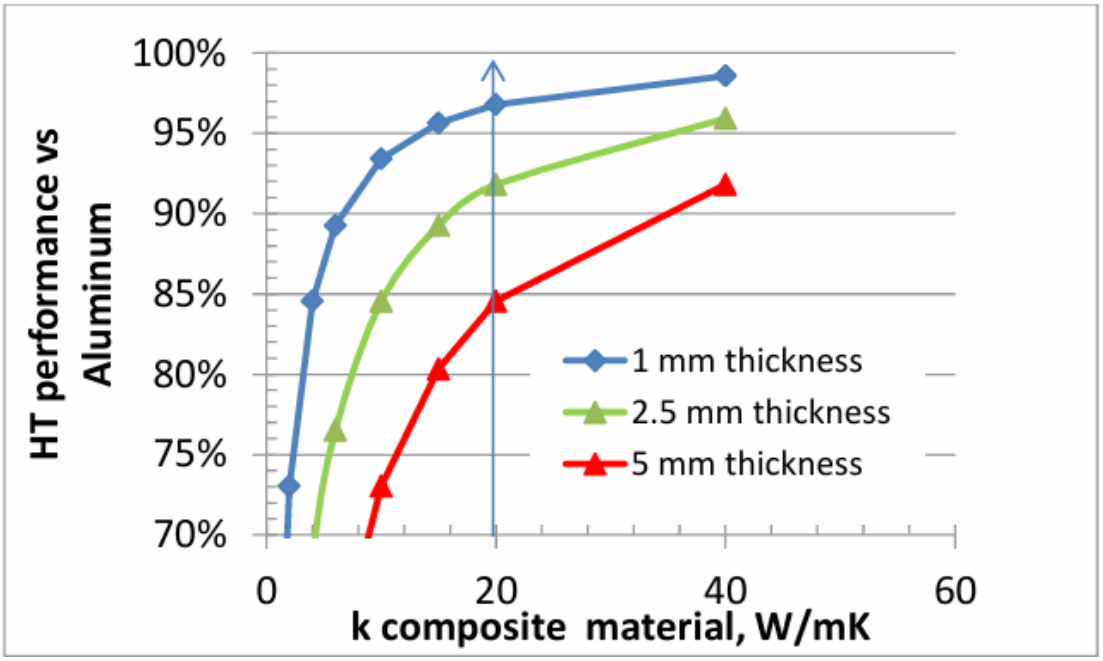


Figure 10 Performance debit versus aluminum (k=180 W/m K) and stainless steel (k=16 W/m K) [20]

Polymers have specific temperature limits. For this purpose, it is important that heat-resistant polymers are used. They are specially designed to maintain their structural integrity and performance at elevated temperatures. These polymers are often used in applications requiring thermal stability. For instance, the most recommended upper limit for PVC pipe is 80°C. Exceeding this temperature may damage the PVC pipe and cause the structure to collapse. That is why initial work on heat-conducting thermoplastics has focused on highly heat-resistant resins like LCP, PPS, PEEK, and polysulfide [21].

While some polymers have good chemical resistance, others may degrade when exposed to certain chemicals. This can limit their use in environments where they may come into contact with corrosive substances.

Polymers may not have the mechanical strength required for certain applications. They may deform under pressure or fail under high stress. Polycarbonate (PC) is considered one of the strongest plastics on the market. It is 200 times stronger than glass and is crack-free.

PEEK is characterized by its strength and thermal stability, making it ideal for applications that require strong mechanical properties or applications that will be exposed to high temperatures.

PVDF is resistant to many chemicals and can act as a dielectric barrier.

Permeability is a measure of a material's ability to transmit liquids, gases, and vapors through the material, and is given as a rate. Permeation is the rate at which a permeant (in this case water) passes directly through a solid (polymer). The permeability coefficient is a measure of the permeation rate and is given as the amount of the permeant passing through a unit area of polymer per unit time. [$\mu g/cm^2 min$] This material property is important for closed systems under pressure such as cooling system in battery.

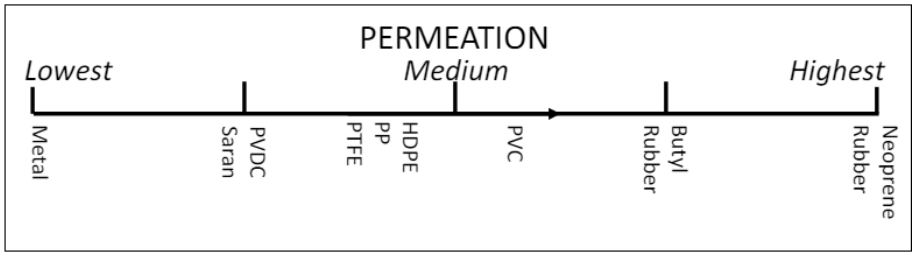


Figure 11 Permeation in polymers

The manufacture of polymer heat tubes can be challenging due to the need for precise control over the properties of the polymer and the design of the heat tube. Processes that are commonly used for manufacturing 3d parts are extrusion, injection molding, blow molding, rotational molding, thermoforming, compression molding. Also, additive manufacturing can be used with ease what would be hard to do and expensive with metals. This way new shapes can be made. Such processes are fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), multi jet fusion (MJF).

By analyzing all properties of the wide variety of polymers it is concluded the most suitable option for manufacturing cooling snake would be polymer composite with fillers that encourage heat transfer. The suitable materials are listed in the table 6. The chosen polyphenylene sulfide PPS E5101.

Table 5 List of suitable polymer composites [20]

Material	Material Supplier	Base Polymer	Density-datasheet (g/cm^3)	In Plane Datasheet (25°C)	Through Plane Datasheet (25°C)	Ultimate Flex. Strength-datasheet (MPa), 25C	Flexural Modulus-Datasheet (MPa) 25C	Ultimate Tensile Strength-datasheet (MPa), 25C	Tensile Modulus-Datasheet (MPa) 25C
E5125	Cool Polymers	PPS	1.72	30	8.88			45	10500
E5501	Cool Polymers	LCP	1.72	35	10.4	48	8100	32	6100
D5506	Cool Polymers	LCP	1.8	10	N/A	84	12300	50	10900
E1201	Cool Polymers	PP	1.24	10	N/A	37	5410	22	5620
E5101	Cool Polymers	PPS	1.7	20	N/A	70	13000	45	13000
E5103	Cool Polymers	PPS	1.54	8	N/A	84	10100	49	11600
E5111	Cool Polymers	PPS	1.71	2.5	N/A	185	15400	110	18300
D5108	Cool Polymers	PPS	1.82	10	N/A	69	19400	37	23600
Pure PPS	McMaster Carr	PPS	1.36	0.3	0.3	N/A	N/A	N/A	N/A

Chapter I I I

CFD Simulation

CFD stands for Computational Fluid Dynamics. It is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems related to fluid flow (liquids and gases). CFD is used to simulate and predict the behavior of fluid flows in various scenarios. Fluid flow is mathematically described using partial differential equations. These equations are then discretized and solved using numerical methods to obtain approximate solutions. Simulations using CFD provide valuable insights into fluid dynamics, allowing for design optimization and informed decision-making without the need for expensive and time-consuming physical experiments. ANSYS Fluent is a software package for fluid flow simulation that falls under the broader framework of ANSYS software tools. ANSYS Fluent enables the execution of CFD simulations for various applications, from aerodynamics to thermal analyses.

For the purpose of this analysis battery cells from formula student team FESB Racing will be used.

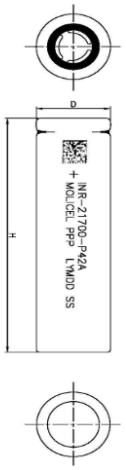
Physical model

Battery

For the purpose of this analysis battery cells from formula student team FESB Racing will be used. These battery cells are used in battery package of electric formula car. Any other cylindrical cells could be cooled the same way with the change in the dimensions of cooling snake.

Table 6 Characteristics of the battery cell

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



Shape	Cylindrical
Can	Steel
Diameter	21.7 mm (Max)
Height	70.2 mm (Max)
Weight	70 g (Max)

Only part of the battery package on which simulation is made is modeled. It is only necessary to model the battery cells which are in direct contact with the cooling snake. The comparison between materials is being made and therefore real size and number of the cells is not very important. 36 cells are used for the simulation and are set in 4 rows with the average distance of 2.5 mm between each of them.

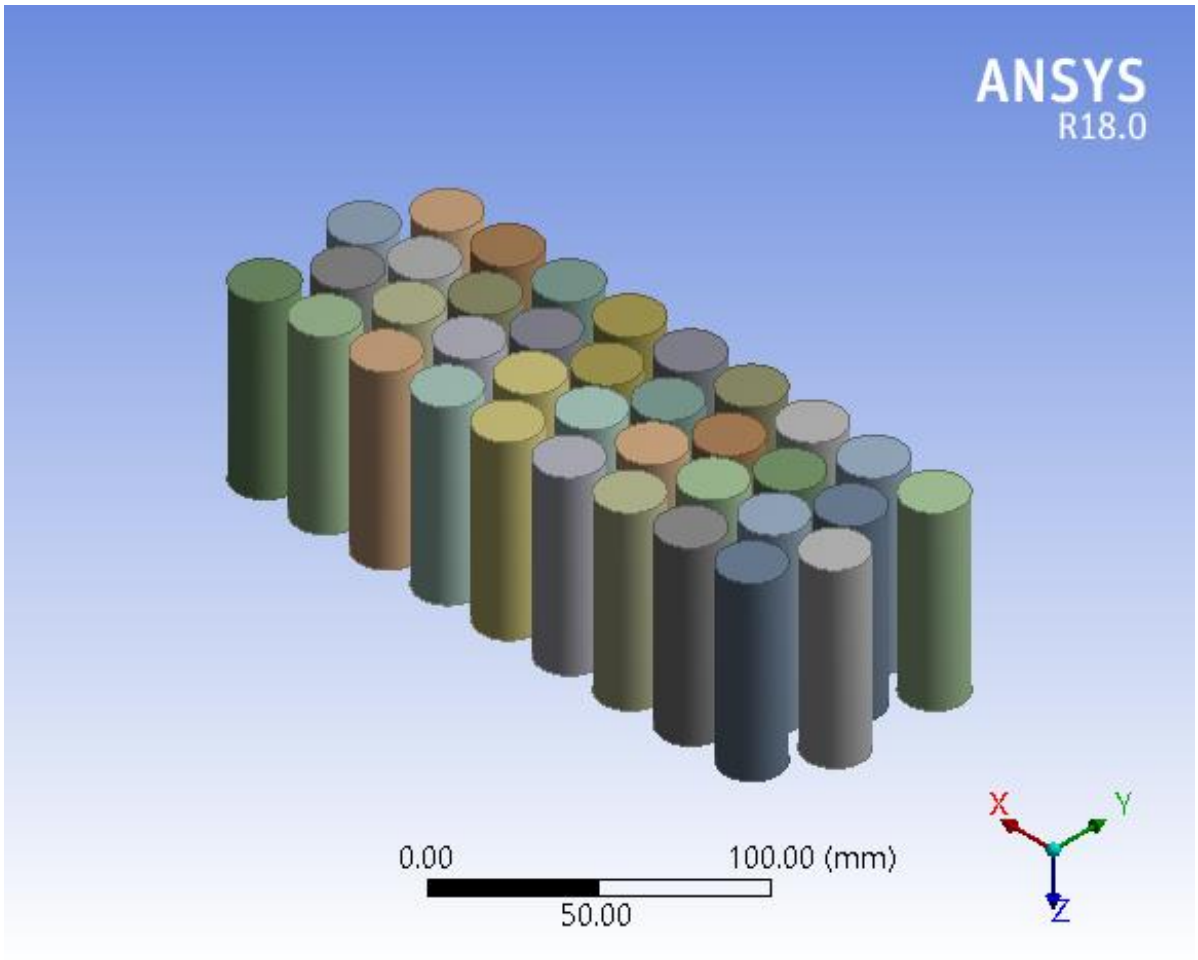


Figure 12 Model of the battery cells

Cooling snake

The model of the cooling snake is made according to the dimensions of the battery cells. Curvature is made so every cell is touched by the snake so that there is conduction between them. Thickness of the aluminum sheet from which the snake is made is 0.7 mm. The same will be used in simulations with polymers so that the comparison is only between different materials and all other factors stay the same. Figure 14 shows dimensions of the modeled cooling snake:

$a_1 = 255\ mm$
$a_2 = 43.7\ mm$

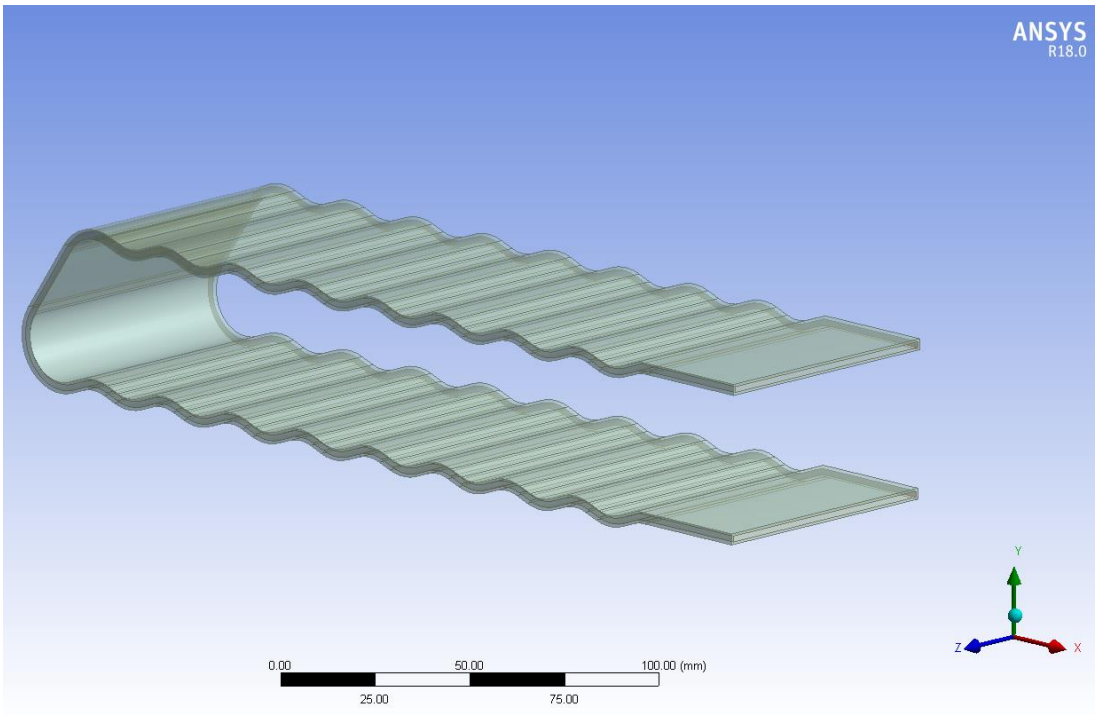


Figure 13 Isometric view of the model of the cooling snake

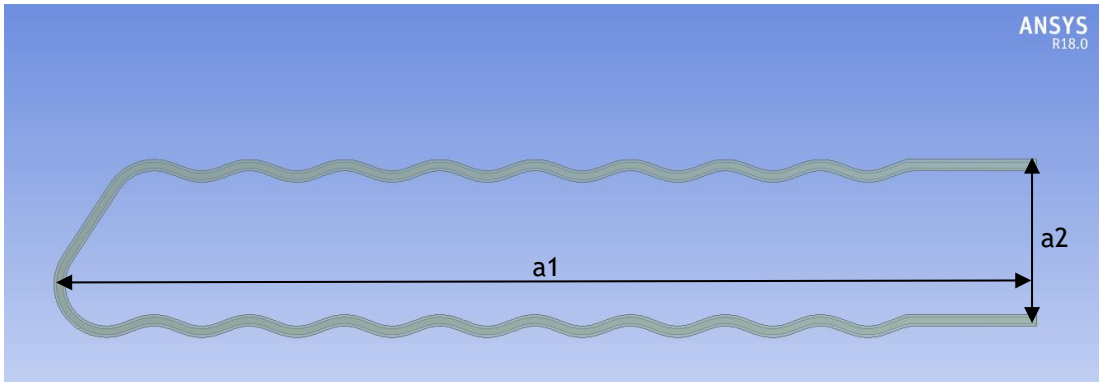


Figure 14 Model of the cooling snake

On the figure 15 detail of the cooling canal is shown with the dimensions:

$m_1 = 3\ mm$

$m_2 = 1.6\ mm$

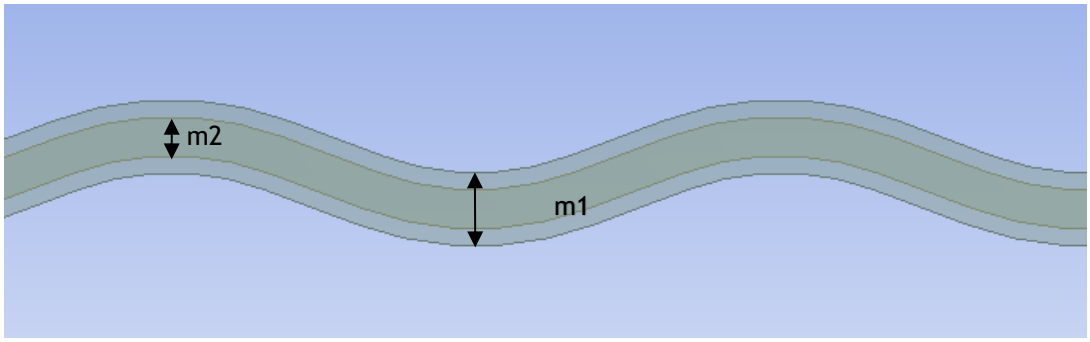


Figure 15 Detail of the canal of the cooling snake

Fluid (water)

The model of the fluid (water) is made by intersecting with the model of the aluminum snake so it is entire cooling canal (inside of the cooling snake) with the same dimensions as it.

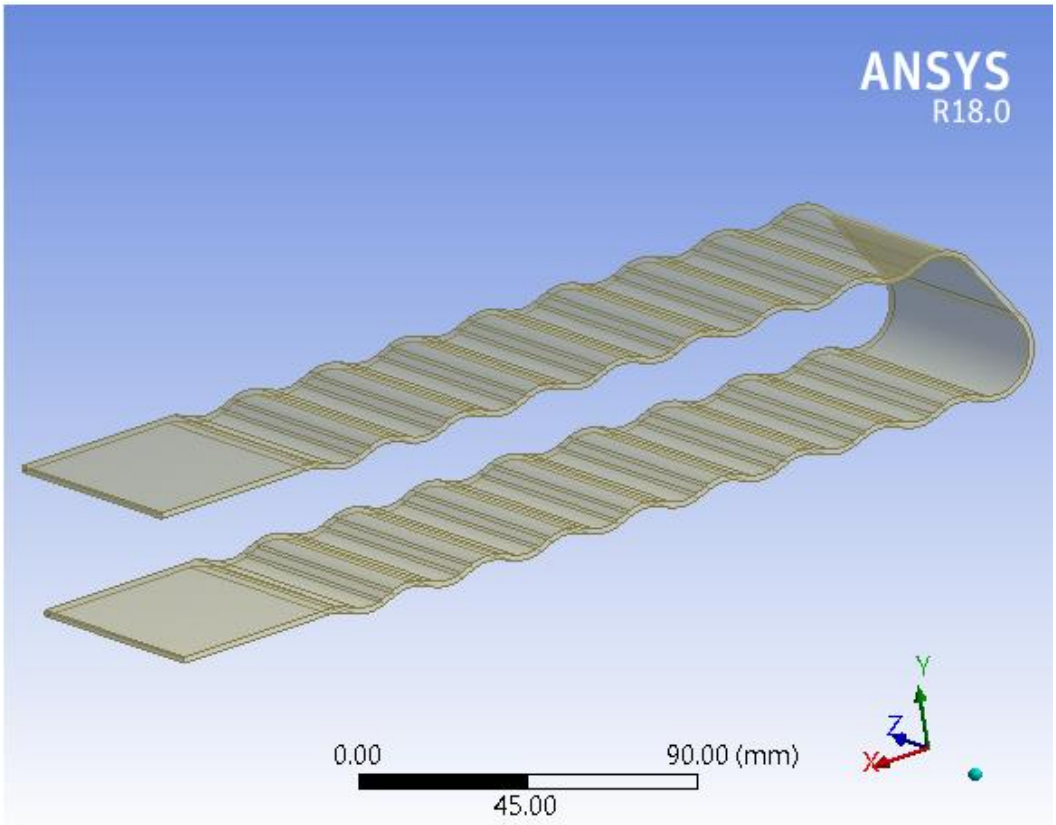


Figure 16 Model of the fluid (water)

On the figure 17 whole model of the batteries and cooling snake with the water is shown. Battery cells are laying on the snake in the specially made groves.

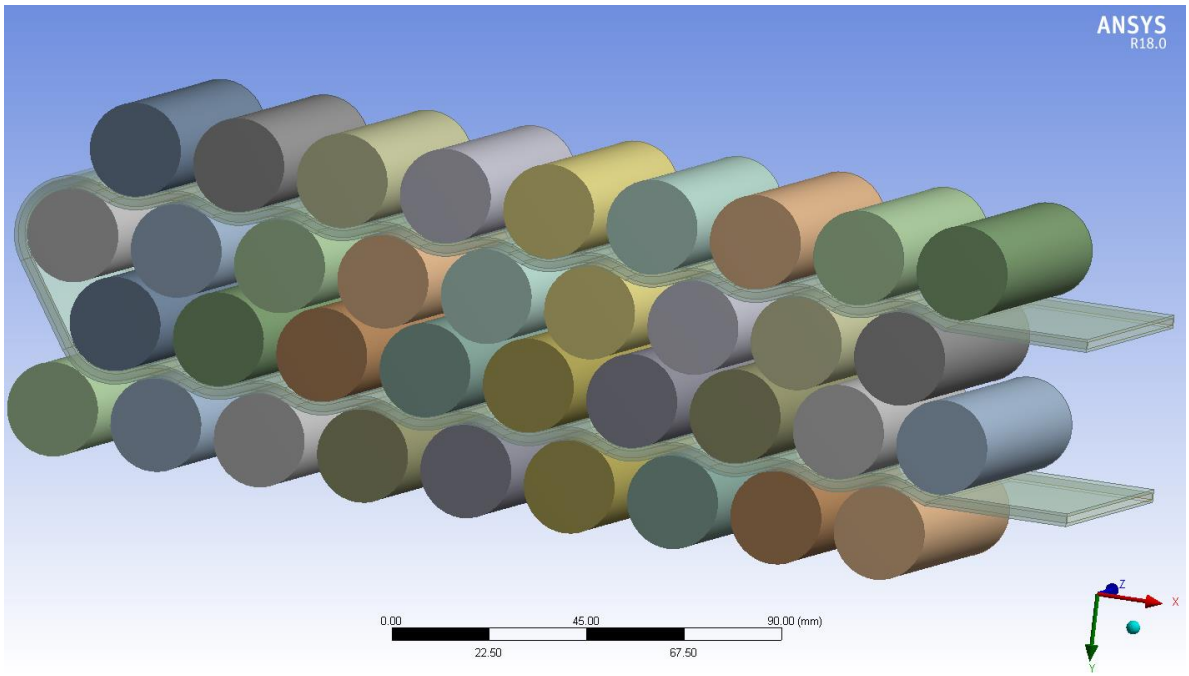


Figure 17 Complete model of the battery with cooling snake

Mesh

For the simulation it is not necessary to mesh the batteries because we know heat that they are giving away, more about that in the chapter *"Set-up"*
Only the snake and water is meshed. To have the quality simulation mesh had to be fine because of the small dimensions being used but not too fine so that the simulations would not take too much time. On each interface of the water and snake, elements of the mesh have to be small so that the boundary layer can be correctly simulated. This is resolved by using inflation which gives smaller elements on the face which grow bigger when going to the middle of the body, as it can be seen on the figure 19.

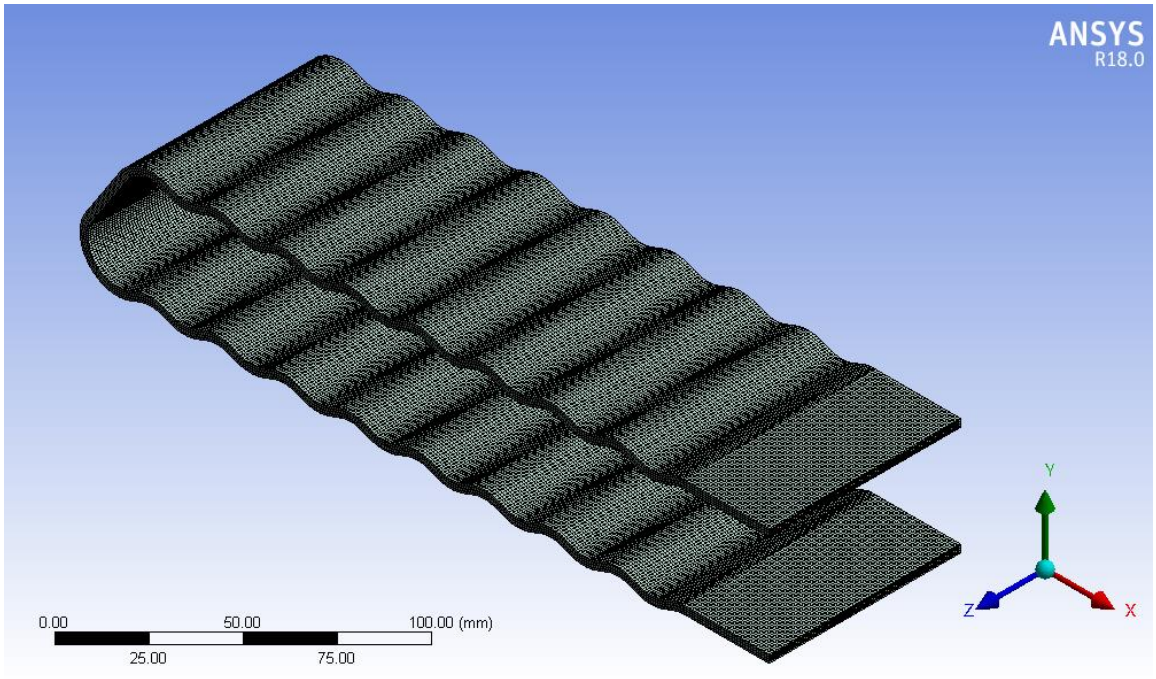


Figure 18 Meshed model

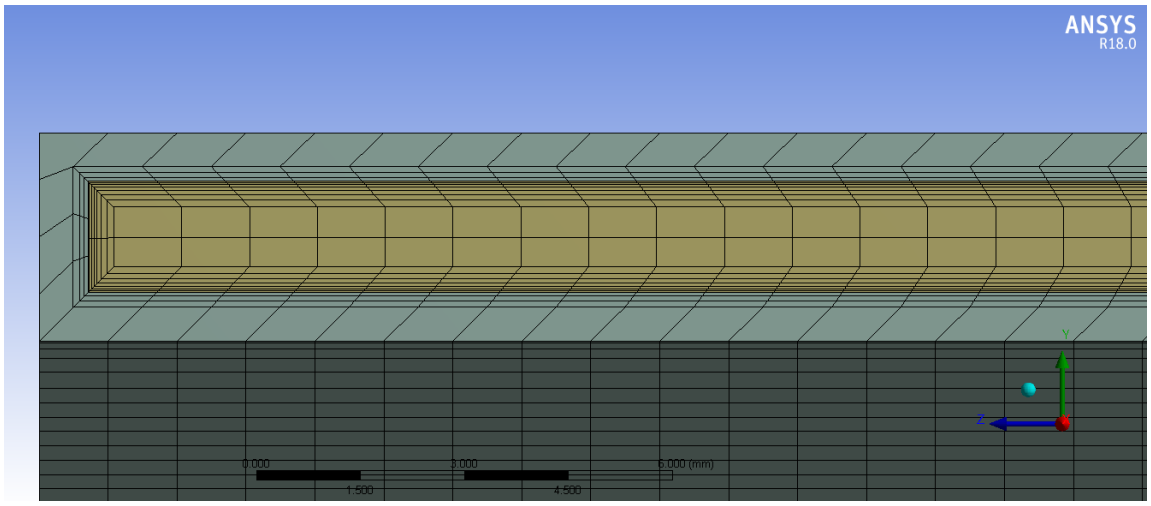


Figure 19 Detail of the mesh on cooling snake and the water

This results with the mesh that consists of 1 245 766 nodes and 1 104 515 elements.

Set-Up

Model

In this simulation SST k−ω model is used. 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. It is chosen because it correctly predicts flow in the near wall region.

Materials

Water data from Ansys database is used for the material of the fluid:

Table 7 Water datasheet from Ansys

Density	998.2 kg/m^3
Specific heat	4182 J/kg K
Thermal conductivity	0.6 W/m K
Viscosity	0.001003 kg/m s

For the material of the snake Ansys data for Aluminum is used:

Table 8 Aluminum datasheet from Ansys

Density	2719 kg/m^3
Specific heat	871 J/kg K
Thermal conductivity	202.4 W/m K

Battery cell material had to be made from the experimental data:

Table 9 Batteries datasheet

Density	2893 kg/m^3
Specific heat	850 J/kg K
Thermal conductivity	0.3 W/m K

For the polymer material polyphenylene sulfide PPS E5101 from the table is chosen with the selected specifications:

Table 10 Polymer (PPS) datasheet

Density	1700 kg/m^3
Specific heat	1500 J/kg K
Thermal conductivity	20 W/m K

Boundary Conditions

As already mentioned, for the simulation battery cells are not used but only the faces on the cooling snake which they are touching. These faces are shown on the figure 20 in red color. These faces are given boundary condition that there is heat flux of 1320 w/m^2. This number was estimated by experimental work of the FESB racing team. Material added is the one of battery cells and its given wall thickness of 0.01 m to represent that the heat source is in the center of the battery cell.

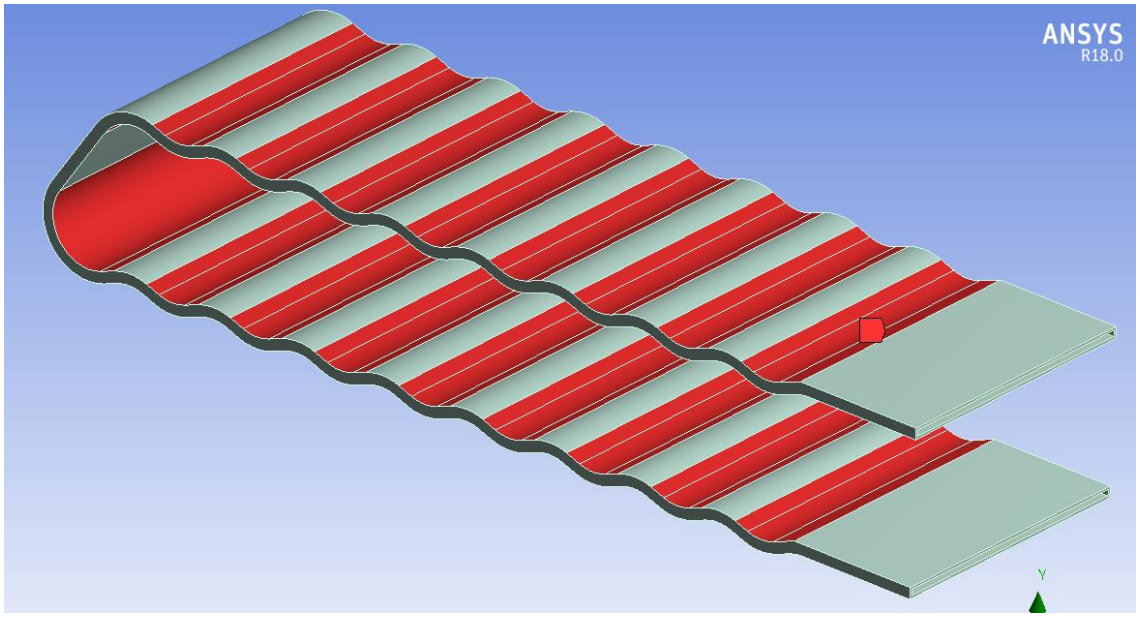


Figure 20 Faces representing interface between the snake and the battery cells

Inlet is characterized by velocity. Because of the dimensions 70.2 mm x 1.6 mm, the cross section area of the inlet and consequently of the whole canal is 0.00011232 m^2. If the volume flow that pump gives is 0.04 dm^3/s but there are 10 modules in the battery pack that need to be cooled so the entire volume flow needs to be divided by 10 which gives the flow in the one cooling snake of 0.004 dm^3/s. To have the velocity, it is needed to divide the volume flow with the area; $\frac{0.000004\ \mathrm{m3/s}}{0.00011232\ \mathrm{m2}} = 0.036\ \mathrm{m/s}$ so the determined velocity of the fluid in inlet is 0,036 m/s. The temperature of the inlet fluid is defined 300 K same as the temperature of the surrounding environment. On the figure 21 inlet and outlet of the water on the meshed model are shown.

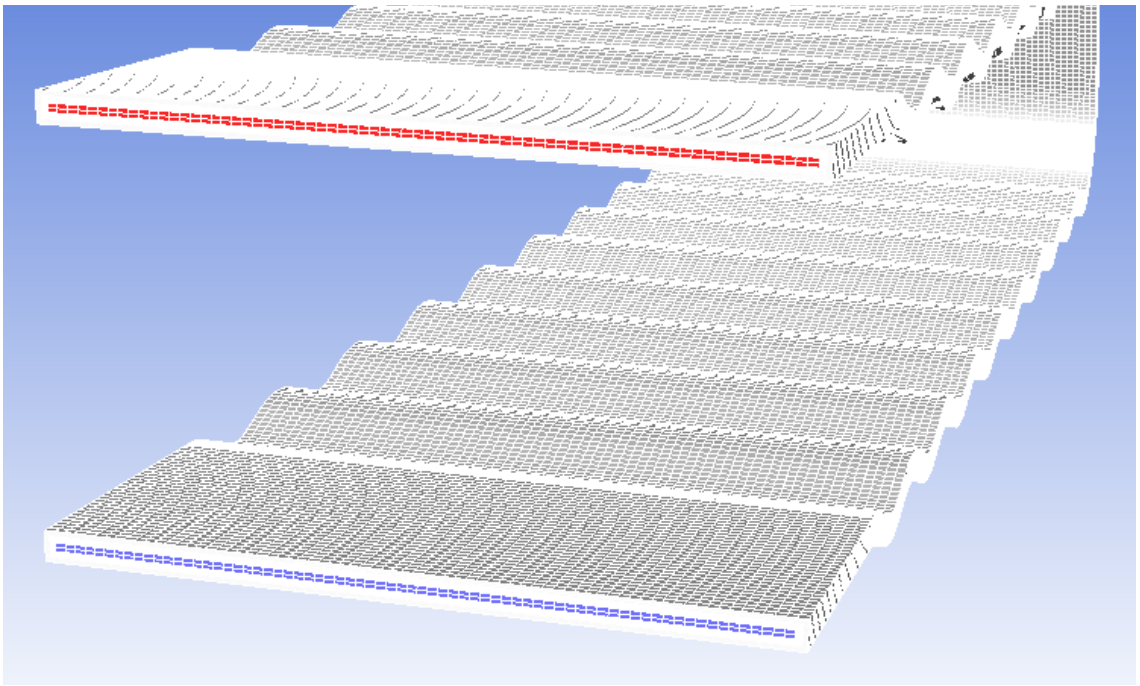


Figure 21 Inlet (blue) and outlet (red)

Simulation results

Both simulations, aluminum and polymer, are done transient. Time step size is 1 second and simulation duration is 60 seconds. Simulation is ongoing until scaled residuals drop below 10^{-6}.

Case 1 – Aluminum cooling snake

Figure 22 shows temperature of the fluid (water) on the outlet. It starts as 300 k and rises to the 304 K after 35 seconds.

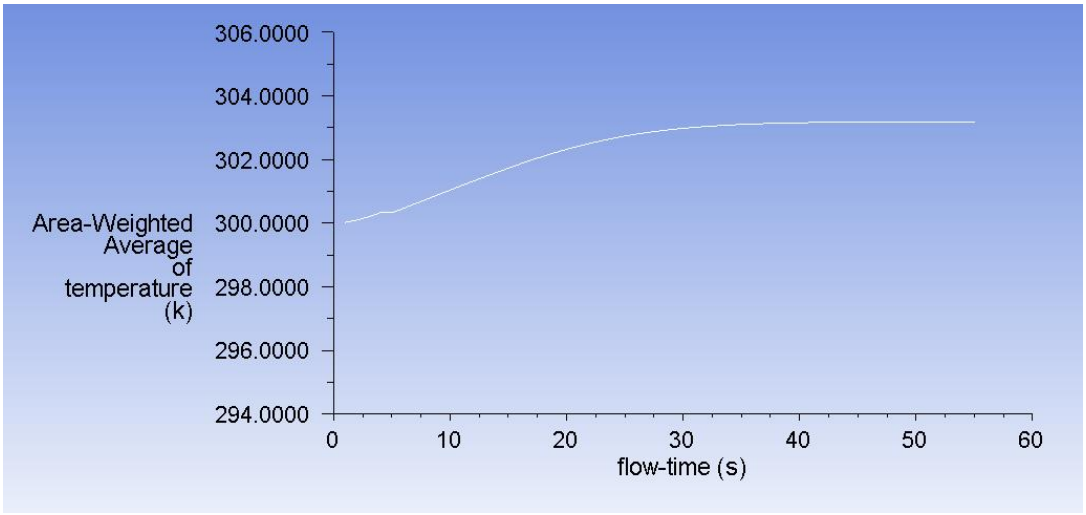


Figure 22 Temperature on the outlet

Temperature gradient on the surface of the aluminum cooling snake is shown on the figure 23. As expected, the coolest part is at the inlet. Water heats up while traveling thought the cooling channel and so the warmest spot is where the last battery cell is placed.

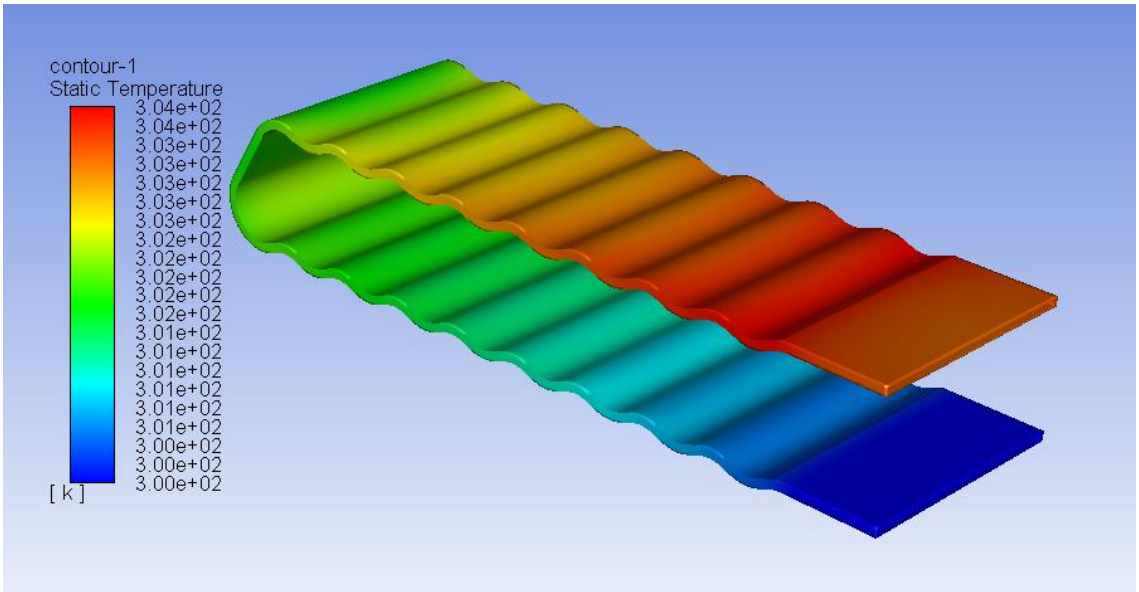


Figure 23 Temperature on the surface of the aluminum cooling snake

Case 2 – Polymer cooling snake

Figure 22 shows temperature of the fluid (water) on the outlet. It starts as 300 K and rises to the 304 K after 35 seconds.

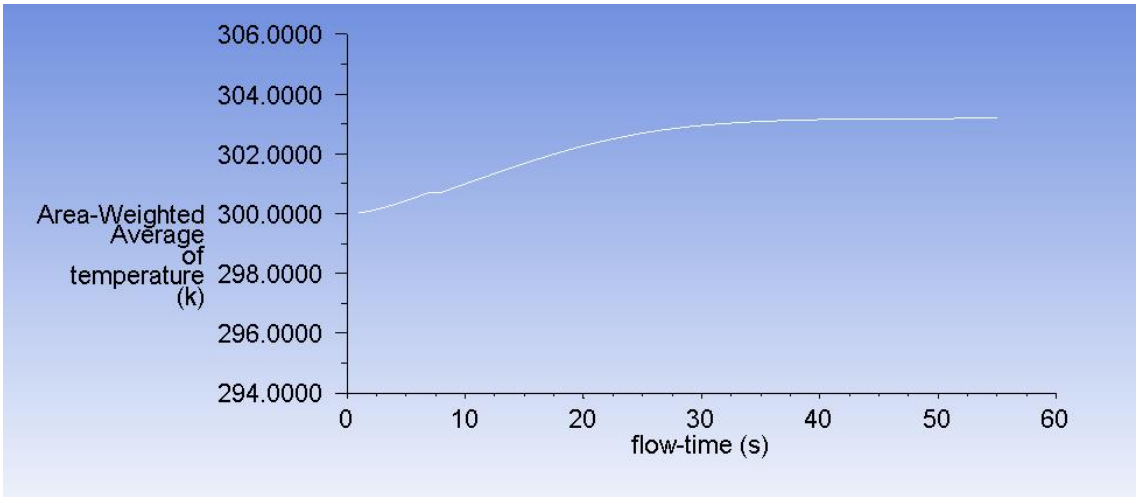


Figure 24 Temperature on the outlet

On the figure 25 temperature of the surface of the polymer cooling snake can be seen. Same as on the aluminum one, the regions closer to the inlet are colder and regions closer to the outlet are hotter. Also, the material is not as uniformly heated which can be observed on the model as the edges are on the higher temperature than the middle of cooling channel.

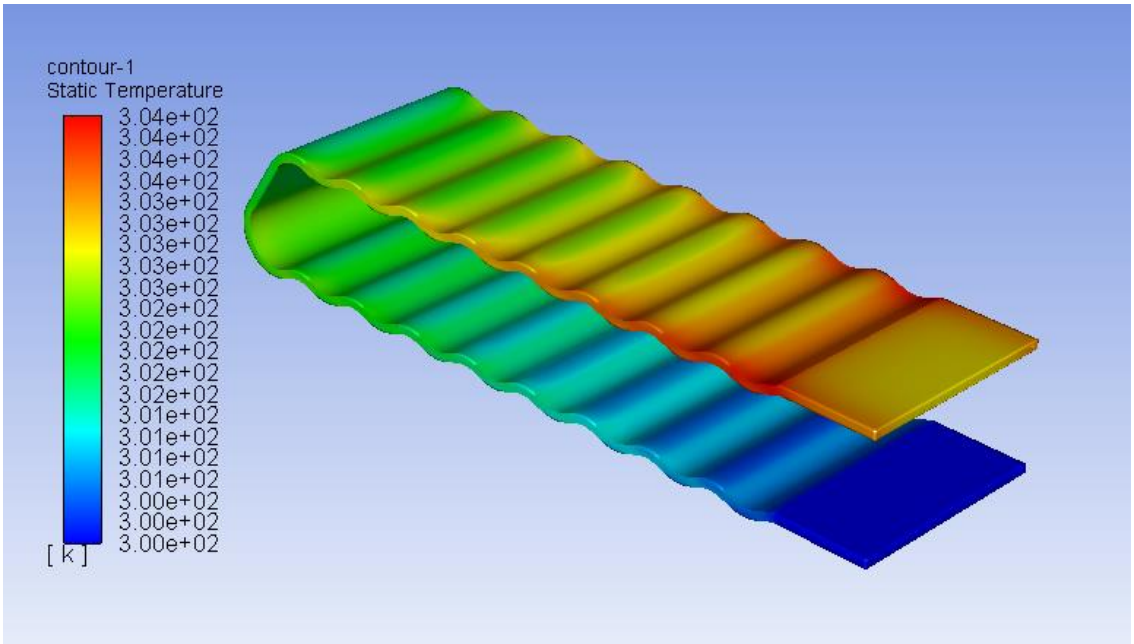


Figure 25 Temperature on the surface of the polymer cooling snake

Conclusion

Management of the battery temperature is of great importance for its health, safety and performance. There is great variety of methods of keeping the temperature under the agreeable limits: air cooling, liquid cooling, PCM, thermoelectric cooling, refrigerant cooling. Considering there are a lot types of batteries (chemical composition and shape vise), only one combination could be closer examined and that was liquid cooling of the cylindrical lithium batteries. Main goal was to compare aluminum cooling channels with the possible polymer replacement material. Diverse set of the properties were taken into account and simulations regarding their thermodynamical performance were done. Both simulations converge to the same temperature of the outlet – 304 K. Only difference between them is temperature uniformity on the surface of the cooling snake. Higher thermal conductivity of the aluminum results in the same temperature across the surface. Lower thermal conductivity results in heat buildup in the corners. Reason why the temperature is same for both materials is that the heat dissipation is not limited by conductivity of the material but with the convection of water. The battery module in question emits too small amount of heat so the both the aluminum and polymer material are good enough. For this purpose, it seems that PPS could replace aluminum regarding thermal properties. The properties of the materials should be reconsidered if the number of battery cells increases in the module or if the battery cells are replaced by more powerful ones. For battery modules sized as this one polymer has its own advantages: because of the differences in density of the materials, weight could be 59% lower. To promote the heat transfer, the wall of the cooling snake could be thinner which would result in even more saved weight. Price of the polymers is fraction of the price of the aluminum and if the possibility of the new manufacturing techniques, such as additive methods, are considered then the replacing material would have great impact from the economic standpoint.

References

[1] How It Works: Battery Thermal Management System; JANUARY 27, 2023 https://www.modineev.com/how-it-works-battery-thermal-management-system/

[2] Charlotte Argue; Electric Vehicles; To what degree does temperature impact EV range? November 30, 2023, https://www.geotab.com/blog/ev-range/

[3] WHAT IS LIQUID-COOLED BATTERY COOLING?; April 1, 2022 https://www.tycorun.com/blogs/news/what-is-liquid-cooled-battery-cooling

[4] 3 Cooling Methods for Energy Storage Battery Pack Thermal Management https://www.lneya-online.com/3-cooling-methods-for-energy-storage-battery-pack-thermal-management.html

[5] Huanwei X, and others, Optimization of liquid cooling and heat dissipation system of lithium-ion battery packs of automobile, Case Studies in Thermal Engineering, Volume 26, 2021

[6] Henkel's Electric Vehicle Battery Technologies Dominate the News; September 16, 2019 https://www.adhesivesmag.com/blogs/14-adhesives-blog/post/97213-henkels-electric-vehicle-battery-technologies-dominate-the-news

[7] When It Comes To Water Pumps, EVs Are Business As Usual; June 6, 2019 https://www.aftermarketnews.com/when-it-comes-to-water-pumps-evs-are-business-as-usual/

[8] https://www.mahle.com/en/products-and-services/commercial-vehicles/cooling/

[9] https://www.mersen.com/products/solutions-power-management/cooling-solutions/liquid-cooled-cold-plate-heat-sink

[10] https://www.trumony.com/E-Mobility-Cooling-Solution-NMC-Lithium-Battery-Cooling-Aluminum-Liquid-Cooling-Plate-pd44233150.html

[11] Pivac Ivan, Prijenos toline i tvari,(Heat and mass transfer) FESB, University of Split

[12]MatWeb
https://www.matweb.com/search/DataSheet.aspx?MatGUID=0cd1edf33ac145ee93a0aa6fc666c0e0&ckck=1

[13] Aluminium: Specifications, Properties, Classifications and Classes; May 17 2005
https://www.azom.com/article.aspx?ArticleID=2863

[14] Gruss, Jean & BOUZON, CHRISTOPHE & Thonon, Bernard. (2005). Extruded Microchannel-Structured Heat Exchangers. Heat Transfer Engineering. 26.

[15] What is Aluminum Extrusion?
https://www.gabrian.com/what-is-aluminum-extrusion-process/

[16] https://www.chaluminium.com/aluminium-tube/aluminium-multi-channel-tube

[19] Dimensionally stable plastics

https://www.ensingerplastics.com/en-us/shapes/plastic-material-selection/dimensionally-stable

[19] Lilli Manolis Sherman, Plastics That Conduct Heat https://www.ptonline.com/articles/plastics-that-conduct-heat

[20] Thibaud-Erkey, Catherine, Alahyari, Abbas Final Report for Project titled High Thermal Conductivity Polymer Composites for Low-Cost Heat Exchangers

[21] Dimensionally stable plastics
https://www.ensingerplastics.com/en-us/shapes/plastic-material-selection/dimensionally-stable