ARMOUR COLLEGE OF ENGINEERING
ILLINOIS INSTITUTE OF TECHNOLOGY
IPRO 497

LITHIUM ION BATTERY COOLING APPLICATION IN FAST CHARGING PROCESS

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I. Introduction

The decrease in global supply of fossil fuels, and the increasing awareness and regulations of vehicle emissions has pushed for the production and optimization of electric vehicles (EV). At first there were several challenges with electric vehicles, like price, range, and accessibility to charging. However, with rising demand, this industry has boomed and overcome all these challenges. Currently, there are several fully electric vehicles on the road that have a starting price of $35,000 which is a reasonable price for a brand new vehicle. Furthermore, there are now several vehicles that have a range of more than 200 miles on a full charge which compares to the range of a vehicle with a small tank. Finally, there are electric charging stations all over the country that work like gas stations, and there are brand specific stations like Tesla's which allow a person to travel almost anywhere in the country without running out of charge.

Nonetheless, there is still a huge issue that is halting the industry- charging time. The average electric car can take up to 10 hours for a full charge. However, supercharging and quick charging stations have expanded throughout the country. These chargers add about 50 or 60 miles of range in about 20 minutes which is more comparable with pumping gasoline for a combustion engine car. Nevertheless, it still does not compare since a combustion engine car can fill up with enough gasoline to drive several hundred miles in less than 10 minutes, while an electric car takes about an hour, at the fastest, to drive about 200 miles.

Most electric vehicles use lithium ion batteries (LIB) as their power source. This is due to their high energy density, high efficiency, charge retention capabilities and long cycling life [1]. However, these lithium ion batteries have high resistance under heavy loads which generates heat. Furthermore, these batteries are tightly packed in battery packs to minimize size. This heat combined with the series or parallel combinations in battery packs leads to excessive rise in pack temperatures and causes to deteriorate the performance of the packs significantly [2]. Hence, the vast majority of car manufacturers avoid this deterioration in cells by limiting the current at the time of charge, which in turn extends the charge time.

In order to ensure that the cells are operating at the desired temperature range an internal cooling system must be added to the battery. This cooling system can be a passive phase-change system or it can be an active cooling system with a flow in the coolant. The rate of flow and the amount of fluid are directly connected to the amount of heat being generated in the cell. In order to determine this we used two methods. The first method was a mathematical approach with estimated values for the worst case scenario. Concurrently, we used Comsol to create a lithium ion battery model. This model allowed us to see where the heat was being generated and how the resistance, current, and flow rate of the coolant would affect the internal temperature of the cells.

Introduction to Lithium Ion Batteries

In order to understand the scope of this research, it is important to understand how lithium batteries work. In a typical LIB there are 5 main layers: current collector, and graphite anode, a separator, a cathode, and another current collector. There is also usually an electrolyte around the separator which consists of a solution of a lithium salt in a mixed organic solvent [1]. The current collectors are usually aluminum and copper. These LIBs have low self-discharge rate that prevents them from losing their charge for a long period of time, and have high voltage and can work on a wide temperature range of operation [3].

The lithium ions flow from one side of the separator to the other which causes the electric current in the battery. Changes at the electrode-electrolyte interface due to reactions of the anode with the electrolyte are considered to be the major source for ageing at the anode [4]. The reductive electrolyte decomposition and the irreversible consumption of lithium ions that takes place at this interface when the electrode is in the charged state causes protective layers to build up which are referred to as a Solid Electrolyte Interphase (SEI). The SEI reduces the life and discharge rate of the battery [4].

The main reason for the overdevelopment of the SEI is the high current going through the battery and the heat generated within the battery. Heat is generated in batteries from activation losses due to interfacial kinetics, concentration losses due to transport of species, and joule heating movement of charged particles [3]. The calculation of this heat generation will be discussed in further detail in the subsequent section.

II. Method

a. Mathematical Modeling

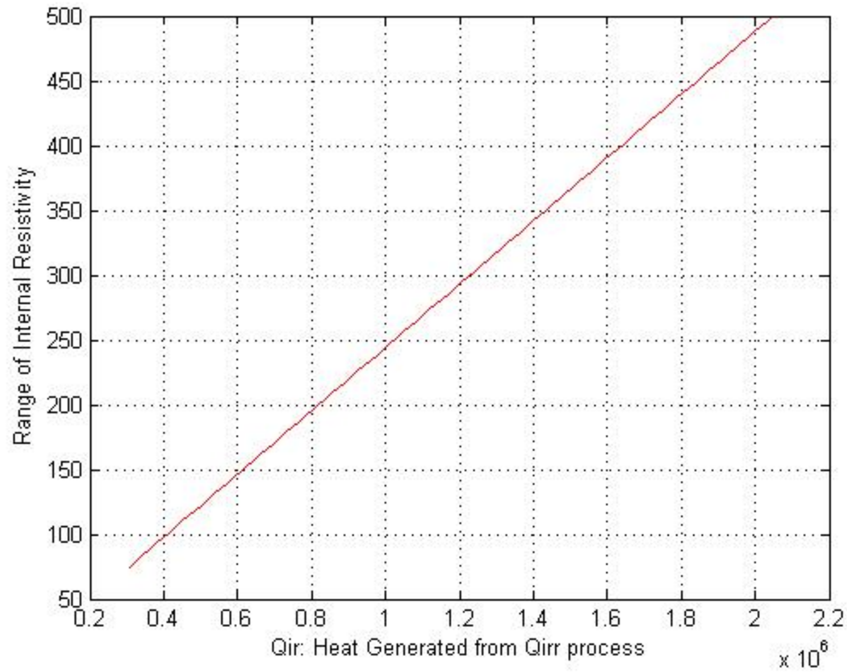
1. Heat generated calculation

To calculate how much heat is generated by a Lithium-Ion battery, we have to take into account the heat generated the irreversible process. The heat generated by the reversible process is ignore because it is negligible. Qirr, the heat generated by the irreversible process by the battery can be calculated by using the following equation

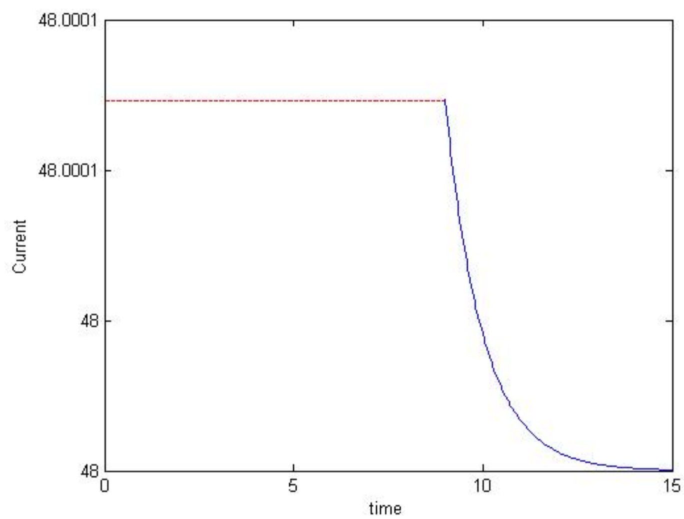
$$Qir = \frac{I^2}{R}$$

Where I is the current applied to the battery, and R is the internal resistance of the battery. The internal resistance of the battery varies with time of charge. The calculation we did is for a small lithium ion battery, specifically All Cell 3.7V 16Ah Battery (http://www.all-battery.com/polymerli-ionbattery37v16000mah80122140-34049.aspx). You can find the dimensions of the battery and the its specs there. Assuming we want to achieve 15 mins time of charge, the maximum heat generated from applying 48 Amps of current, with a 3.6 V battery with a varying internal resistance from 70mΩ to 500 m Ω is 2 KW. Please see MATLAB code for further details.

The graph below shows the relationship between the Qir and internal resistivity



To get an idea on how the current is applied in Lithium Ion batteries, we graphed the current VS Time. The equations are based on the knowledge that current is applied steadily up to 2/3 of the time, and it decreases exponentially for the rest of the time.



2. Head removal calculation

In this calculation, the battery we use to model has the dimensions of 142mm x 124mm x 7.6 mm. The cooling channels locate in between the current collectors of the cathode and anode. The channels has the shape of cylindrical tubes with radius R= 2.5mm, along the 142mm side of the battery. The feed temperature of the coolant is 5°C. In the battery, there are 20 cooling channels. We need to find the velocity of the coolant to maintain the battery at 40°C if the heat generated by the battery is 2048W.

The coolant in this model is Fluorinert Liquid produced by 3M: FC-72. Its properties are:
+Inlet temperature: 5°C
+Density: 1690 kg/m^3
+Heat capacity: 1046.999 J/kg.K
+Absolute viscosity: 0.00064 Pa-s
+Thermal conductivity (k): 0.057 W/m.K
+Number of coolant layer : 5
+Number of cooling channels per layer: 4
+Cooling channels radius (R): 2.5mm
+Cooling channels length (L): 142mm
Assumptions:

1. Heat generation is constant through out the whole battery.
2. The temperature of the battery is the same everywhere in the battery.
3. The head effect is neglected.

Calculations:
To keep the temperature of the battery constant at 40°C, the heat generated is equal to the heat transfer by convection:

$$Q_{convection} = hA\Delta T_{lm}$$

Equation 1.

Where h is the is the average convective heat transfer coefficient in one channel
A is the surface area of each channel
ΔT_{lm} is the log mean temperature difference

The log mean temperature is calculated by

$$\Delta T_{lm} = \frac{\Delta T_o - \Delta T_i}{\ln(\Delta T_o/\Delta T_i)}$$

Equation 2.

$$\Delta T_o = T_s - T_o$$

Equation 3.

$$\Delta T_i = T_s - T_i$$

Equation 4.

where T_s is the battery's temperature
T_o is the outlet temperature of the coolant
T_i is the inlet temperature of the coolant

Since the outlet temperature of the coolant is unknown, we need to solve for ΔT_o:

$$\Delta T_o = \Delta T_i exp\left(-\frac{PL}{v\rho AC_p}h\right)$$

Equation 5.

Where P is cooling channel parameter = $2\pi R$

The average convective heat transfer coefficient (h) in one channel is calculated by

$$h = \frac{Nu \times k}{L}$$

Equation 6.

Where Nu is the Nusselt number
k is the thermal conductivity of the coolant
L is the length of the channel (142mm)

Nusselt number for a turbulent flow is calculated by:

$$Nu = 0.023 Re^{5/4} Pr^{0.3} = 0.023 \left(\frac{\rho v L}{\mu}\right)^{5/4} \left(\frac{C_p \mu}{k}\right)^{0.3}$$

Equation 7.

Where μ is the absolute viscosity

From Equation 1 -7, we have:

$$Q_{convection} = \frac{0.023 \left(\frac{\rho v L}{\mu}\right)^{\frac{5}{4}} \left(\frac{C_p \mu}{k}\right)^{0.3} \times k}{L} A \frac{\Delta T_i exp\left(-\frac{PL}{v \rho A C_p} \frac{0.023 \left(\frac{\rho v L}{\mu}\right)^{\frac{5}{4}} \left(\frac{C_p \mu}{k}\right)^{0.3} \times k}{L}\right) - \Delta T_i}{\ln(\Delta T_i exp\left(-\frac{PL}{v \rho A C_p} \frac{0.023 \left(\frac{\rho v L}{\mu}\right)^{\frac{5}{4}} \left(\frac{C_p \mu}{k}\right)^{0.3} \times k}{L}\right) / \Delta T_i}$$

Equation 8.

Since $Q_{convection}$=2048W, $and\ \rho, L, C_p, \mu, k, A, \Delta T_i = T_s - T_i$ are given above, we solve for v.
We have the velocity of the coolant is: $v = 3m/s$
The average heat transfer coefficient is: h = 1340 W/m^{2}K

b. Software Modeling using COMSOL Multiphysics & Autodesk Inventor Model

1. COMSOL

We used COMSOL Multiphysics to model how the temperature affected battery performance. COMSOL Multiphysics is a general-purpose software platform, based on advanced numerical methods, for modeling and simulating physics-based problems. With COMSOL Multiphysics, you will be able to account for coupled or multiphysics phenomena.

This example simulates a temperature profile in a number of cells and cooling fins in a liquid-cooled battery pack. The model solves in 3D and for an operational point during a load cycle. A full 1D electrochemical model for the lithium battery calculates the average heat source.

The model is based on two assumptions: The first one is that the material properties of the cooling fluid and battery material can be calculated using an average temperature for the battery pack, and the second one is that the variations in heat generation during the load cycle are significantly slower than the heat transport within the battery pack. The first assumption is valid if the temperature variations in the battery pack are small. The second assumption implies that the thermal balance is quasi-stationary for the given battery heat source and at a given operational point during the load cycle.

i. Cell Model

The 1D cell model is identical to the one of a Cylindrical Lithium-ion Battery. The battery temperature is set to the inlet temperature of the cooling fluid. The discharge load is set to a 7.5C rate (a full discharge in 1/7.5 of an hour, 480 s).

ii. Flow and heat transfer model

The model uses the Laminar Flow interface to solve for the velocity and pressure in the cooling channels and the Heat Transfer interface for the temperature field.

Geometry - The repetitive unit cell of the battery pack consists of a cooling fin with flow channels, with one battery on each side, see Figure 1. The cooling fins and batteries are 2 mm thick each, summing up to a total unit cell thickness of 6 mm. Figure 1: Unit cell of the battery pack consisting of two prismatic batteries and a cooling fin plate with five cooling channels.

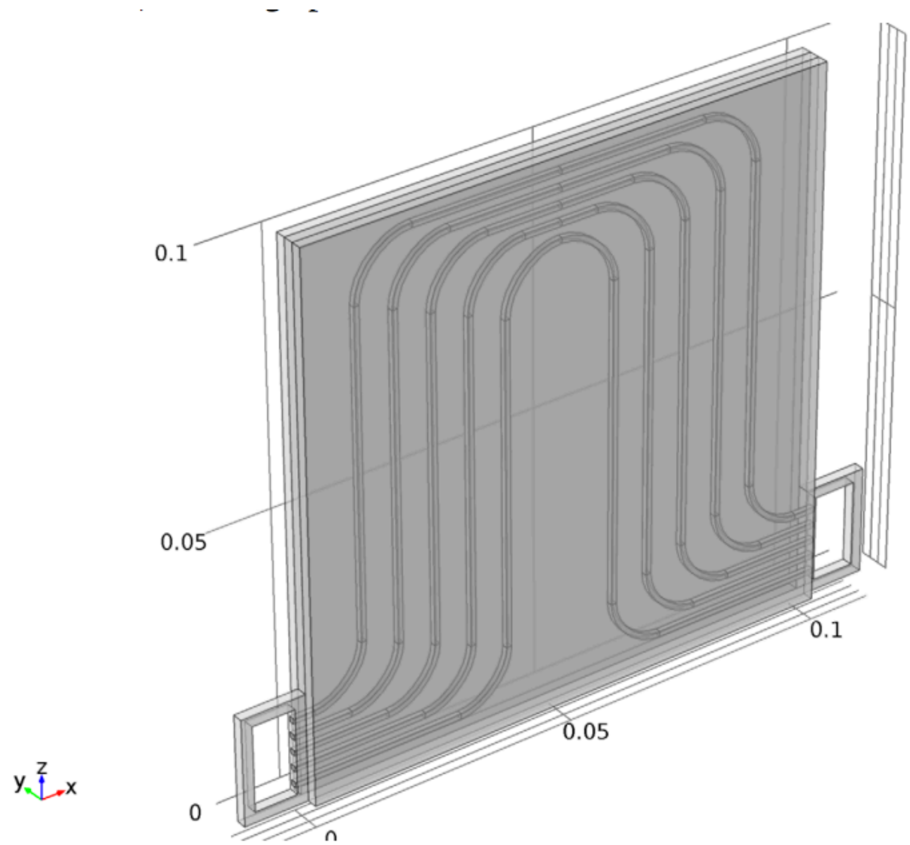


Figure 1: Unit cell of the battery pack consisting of two prismatic batteries and a cooling fin plate with five cooling channels.

The modeled battery pack geometry consists of three stacked unit cells and two flow connector channels: one on the inlet and one on the outlet side of the cooling fins, see Figure 2. The geometry represents the last cells towards the outlet end of a battery pack (the cells of the battery pack not included in the geometry extend from y = 0 in the negative y direction).

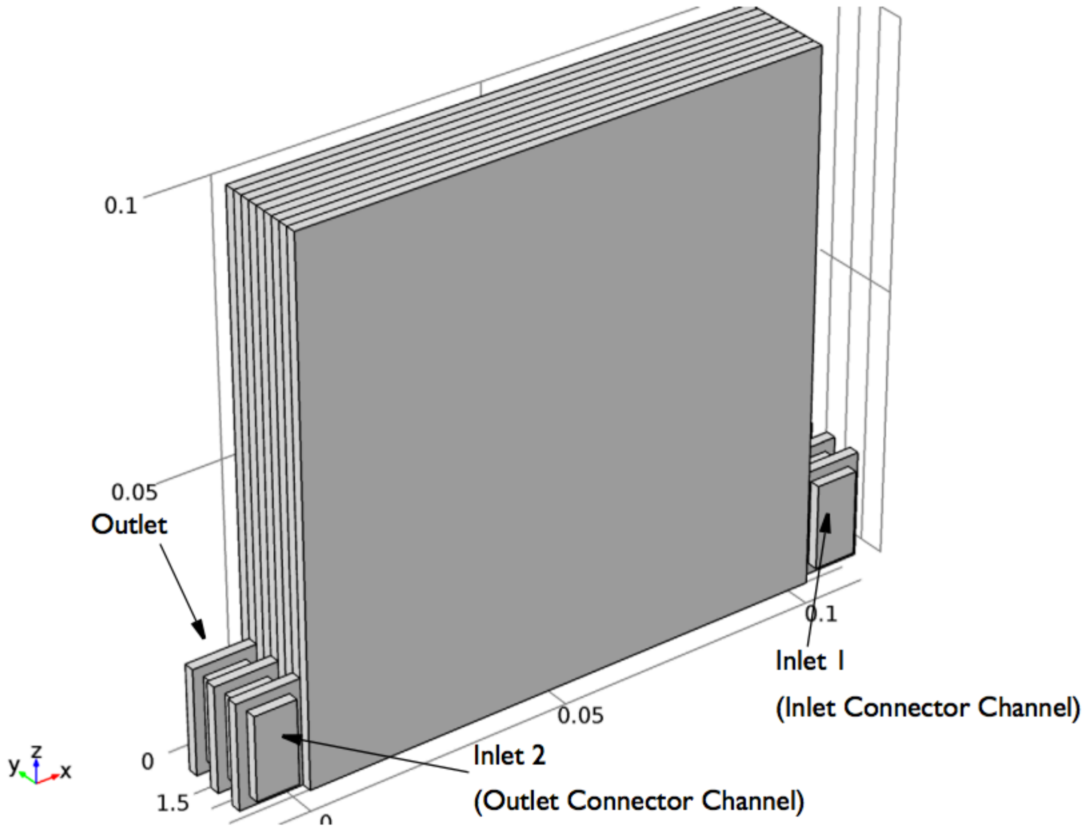


Figure 2: Battery pack geometry. Three unit cells, one inlet connector channel and one outlet connector channel.

The Software user interface

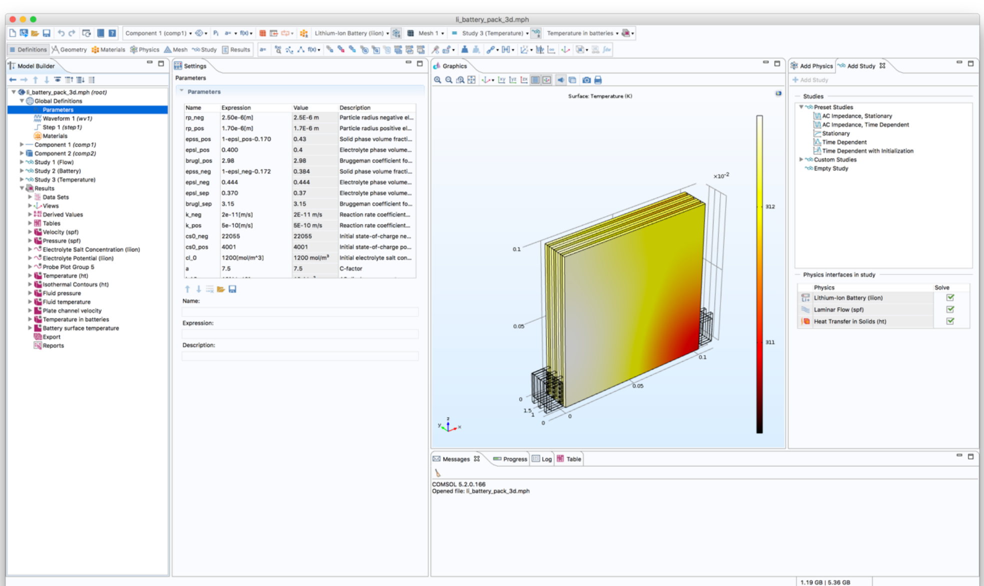


Figure 3: This picture shows the software user interface.

iii. Results and Discussion

Figure 3 shows the pressure in the fluid compartment.

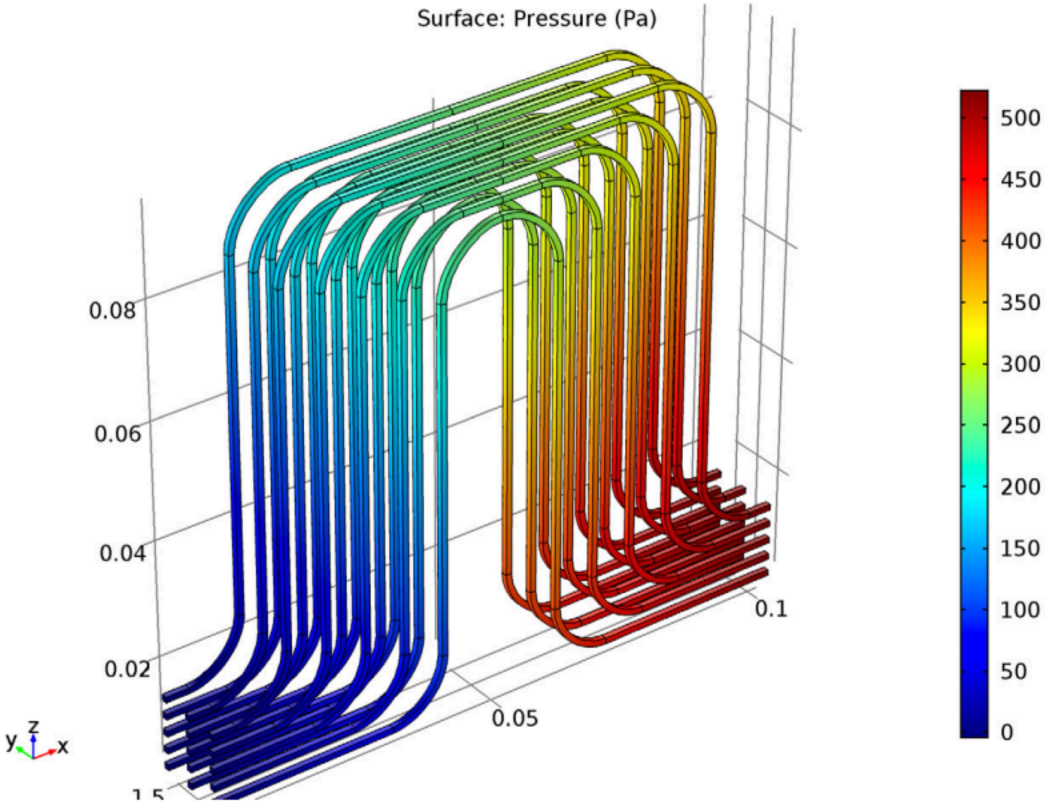


Figure 3: Pressure in the flow compartment.

The velocity magnitude in a cut plane through the middle of one of the cooling fins is shown in Figure 4. The velocity magnitude is about 0.2 m/s in the middle of the channels. This implies that the residence time for the fluid time in the plates is in the range of a only a few seconds, giving support to the assumption that the battery pack reaches a quasi-stationary temperature profile quickly after a load change.

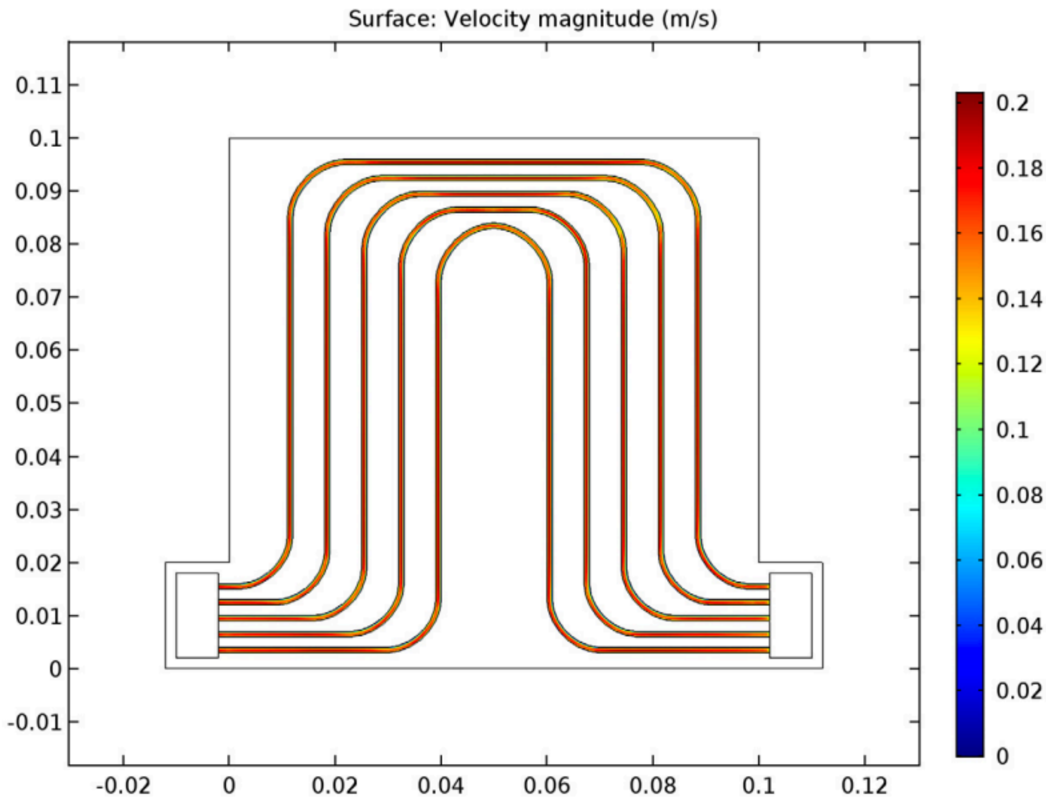


Figure 4: Velocity magnitude in the first cooling fin.

Figure 5 shows the temperature in the batteries. The difference between the highest and lowest temperature in the pack is about 3 K. The temperature variation between different batteries along the y-axis is smaller than the temperature variation within a single battery in the xz-plane.

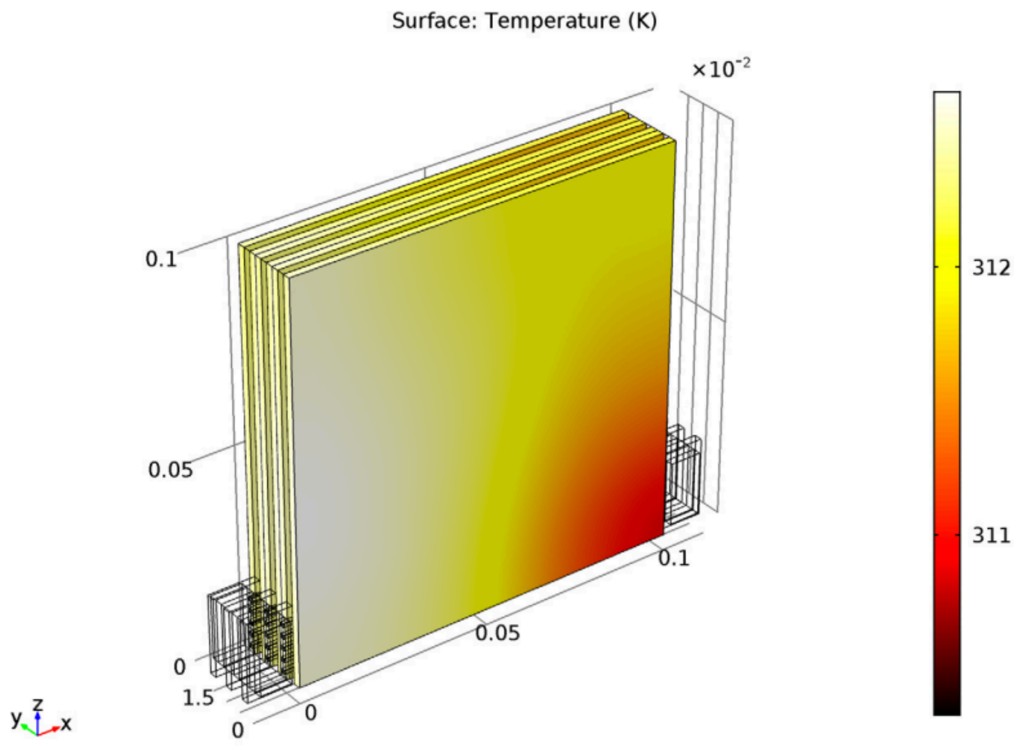


Figure 5: Temperature in the batteries.

Figure 6 plots the temperature of the cooling fluid. The temperatures are slightly lower than in the battery.

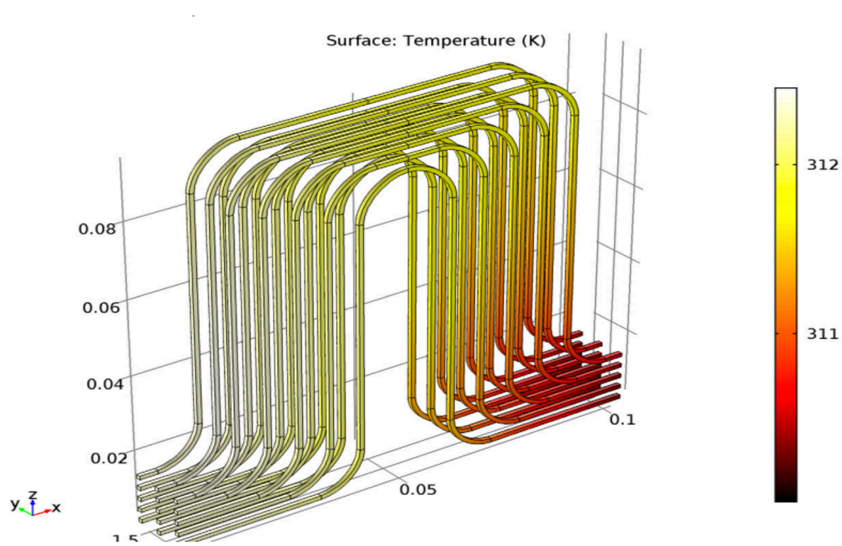


Figure 6: Temperature of the cooling liquid.

Figure 7 shows the temperature in the second battery by comparing the temperature at the surface facing the cooling fin (y = 4 mm) to the surface facing the third battery (y = 6 mm). The surface towards the cooling fin is cooler, reaching a minimum at the corner towards the inlet. The temperature gradient over the battery is also at its maximum at this point.

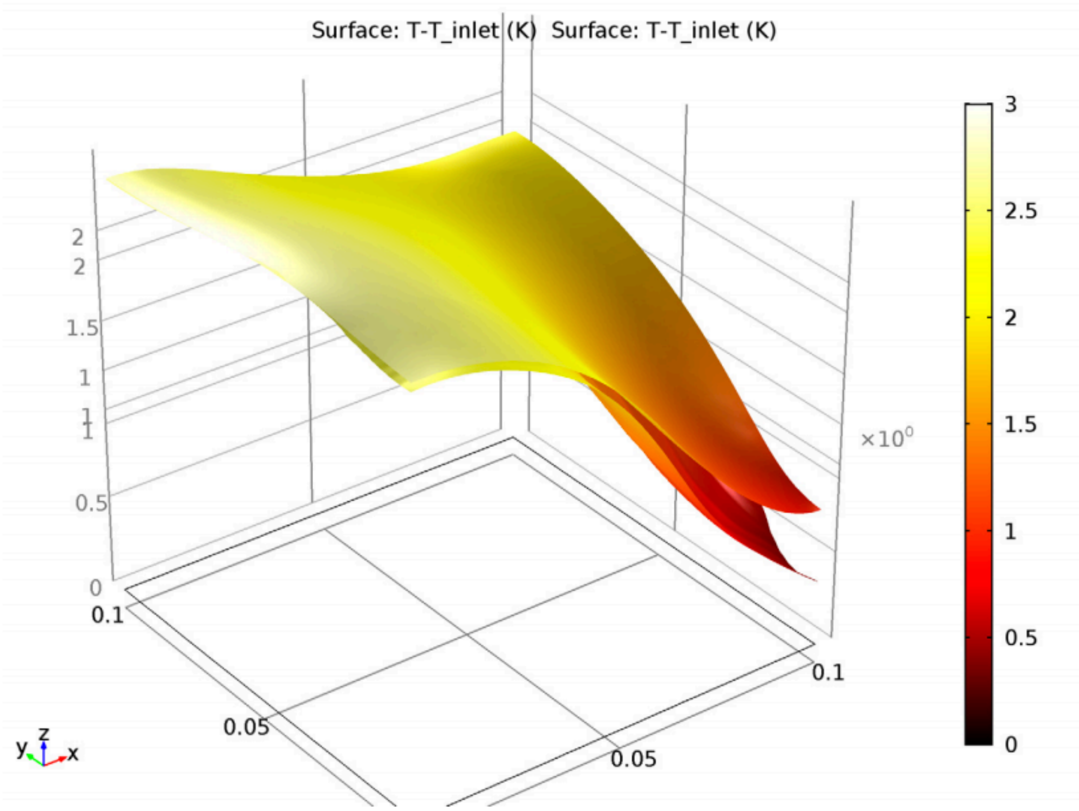
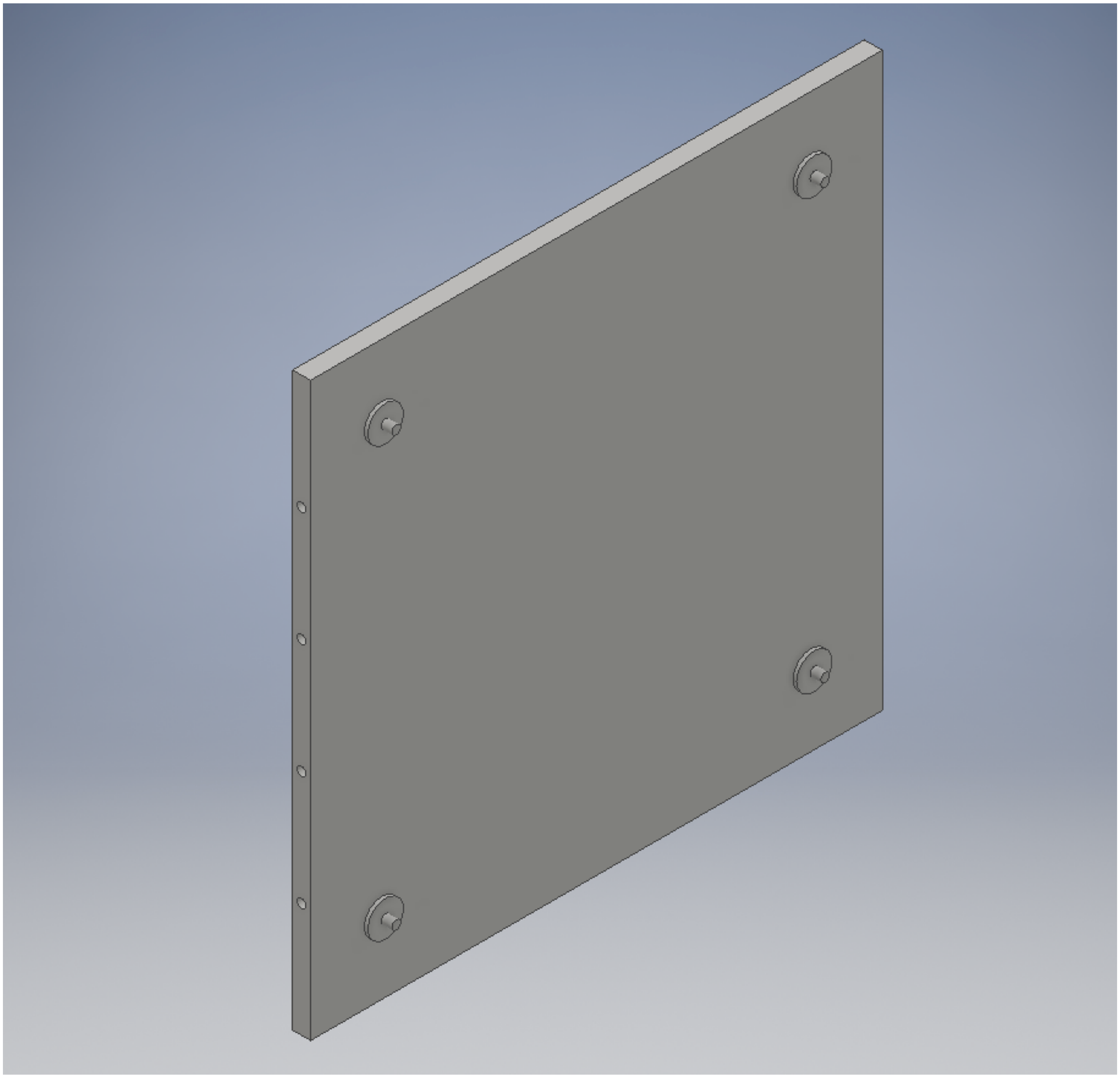


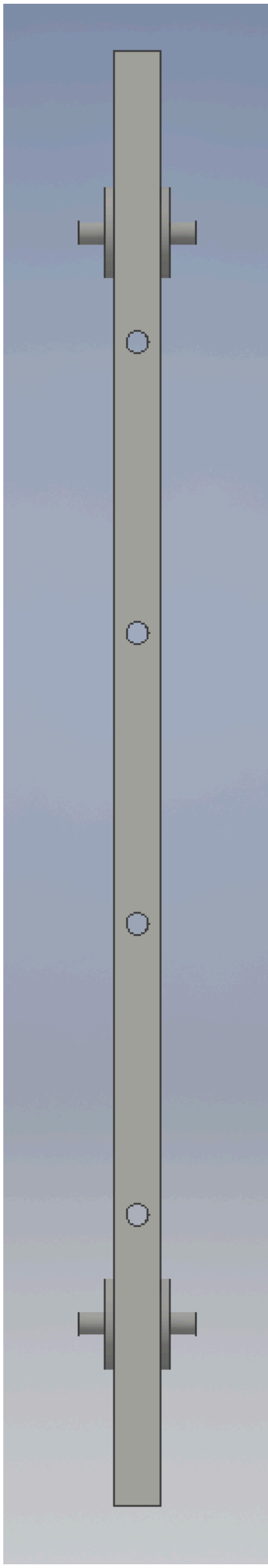
Figure 7: Temperature increase (in relation to the inlet temperature) of the second battery at the surface facing the cooling fin (y = 4 mm) and the surface facing the third battery (y = 6 mm).

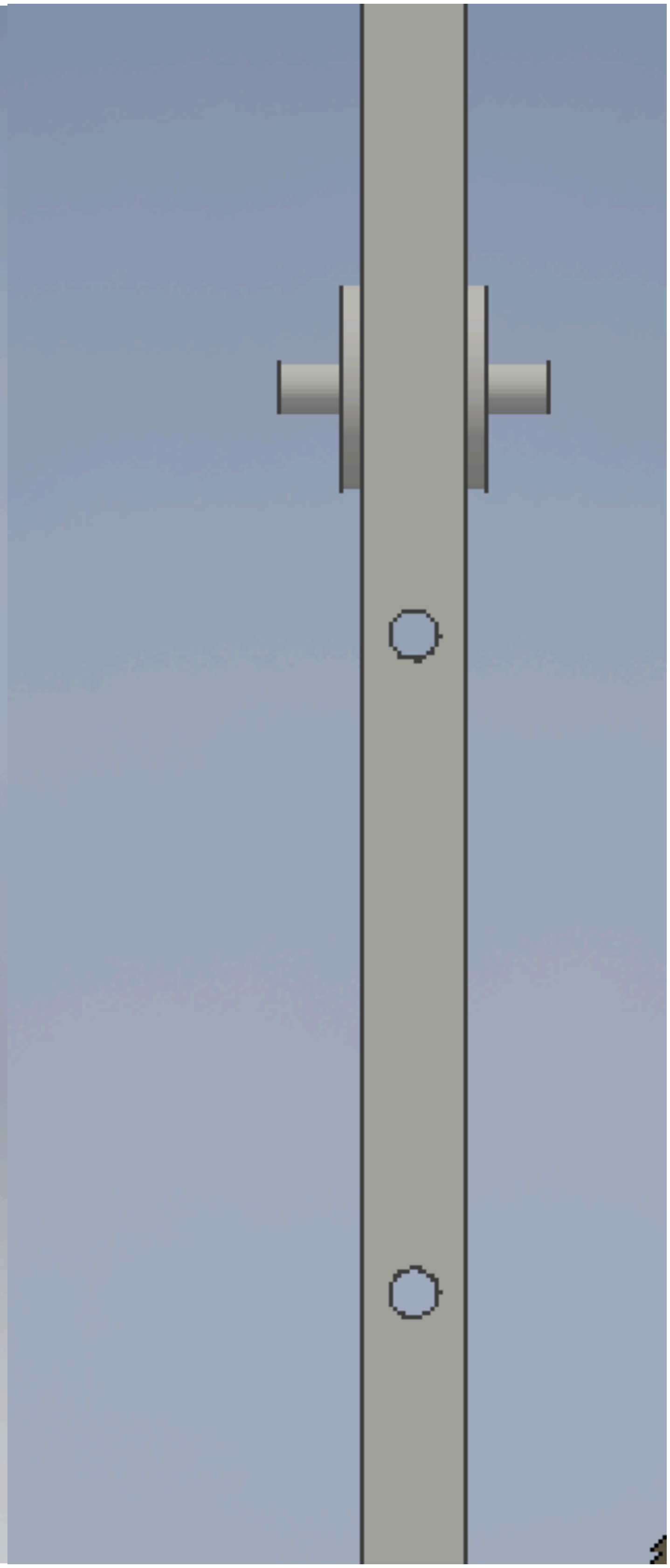
2. Autodesk Inventor

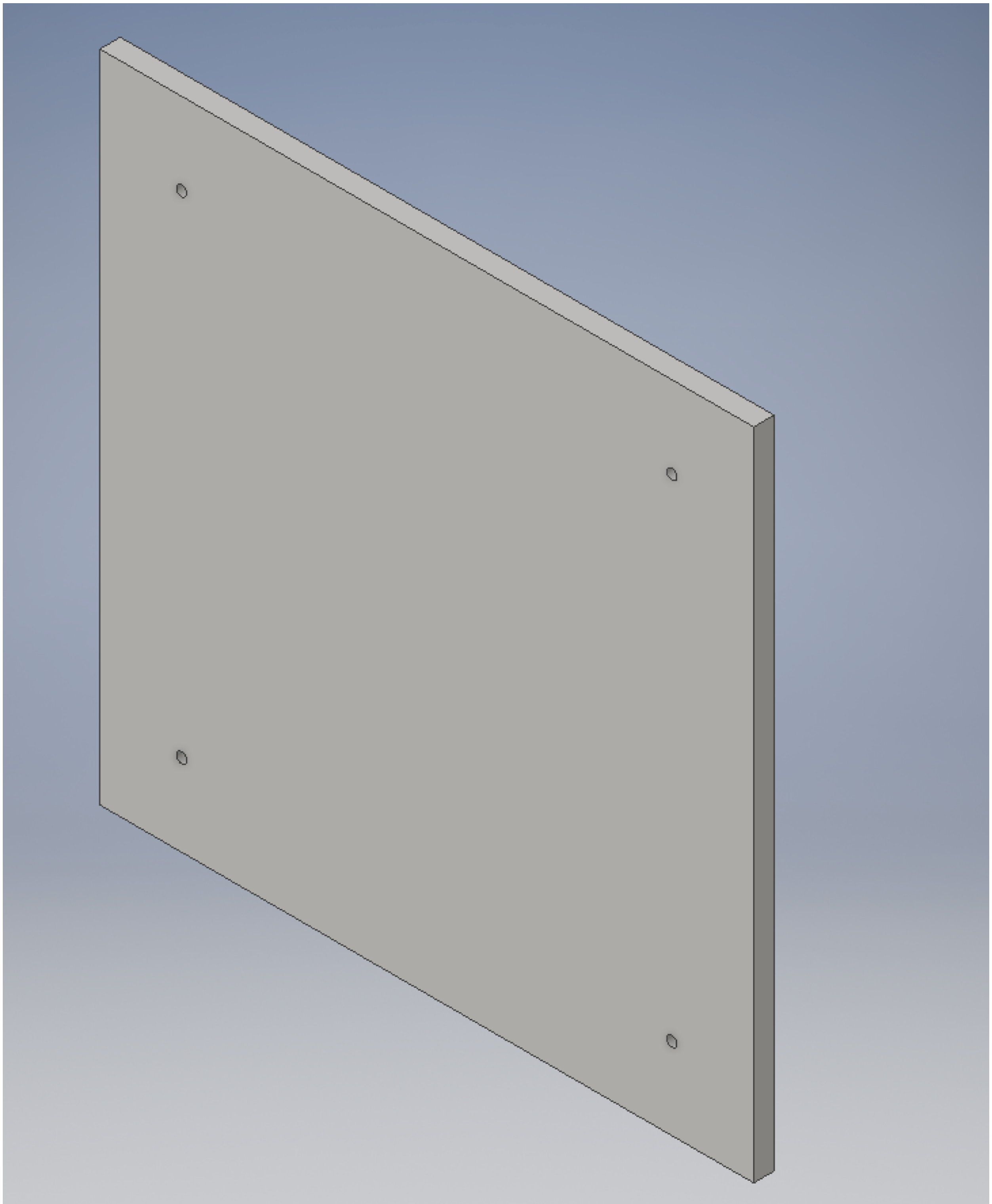
It is a computer-aided design application for creating 3D digital prototypes used in the design, visualization and simulation of products. This is the modelling software we used to model the cooling system for our battery.

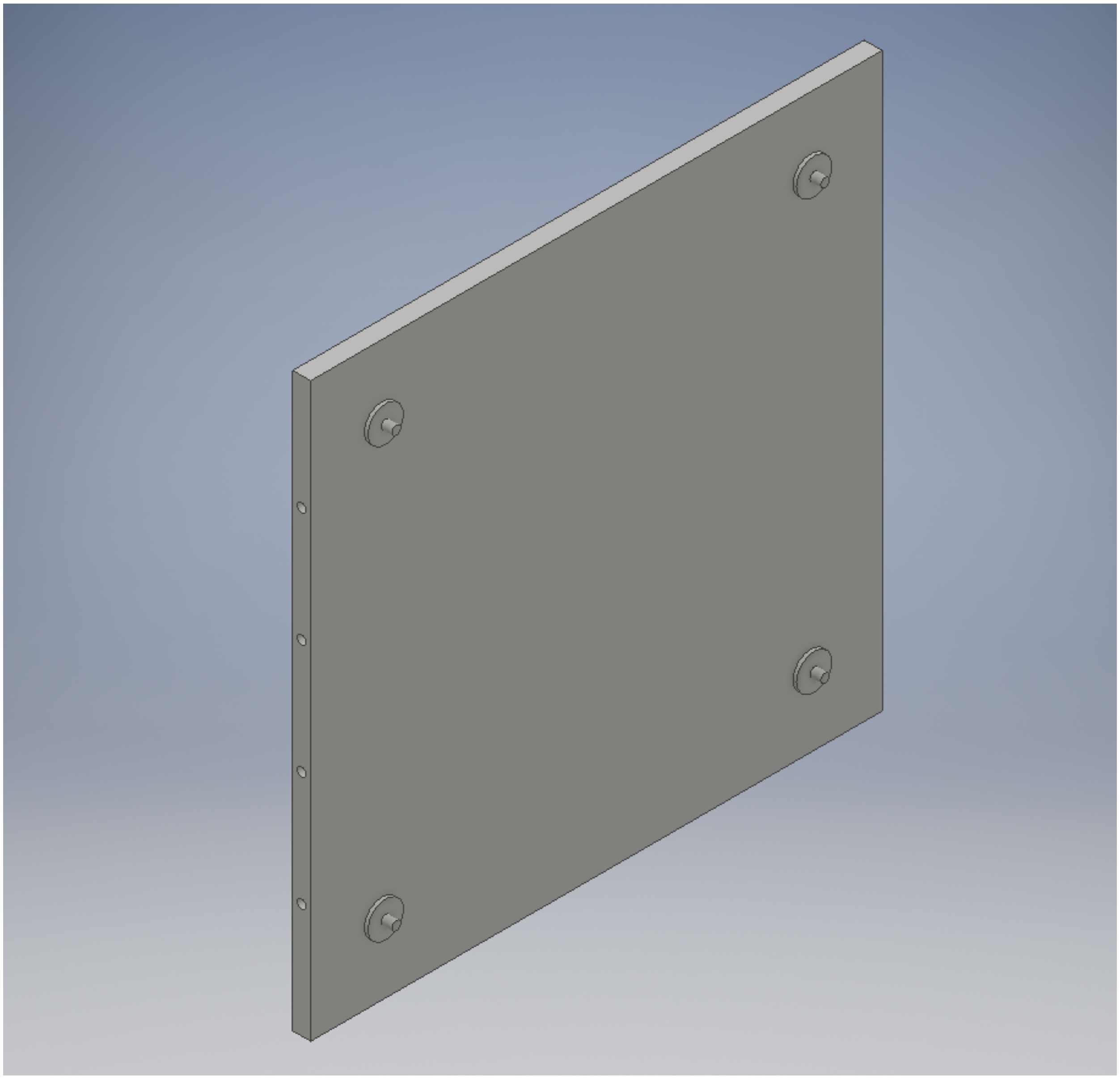
The images below show the model in detail.

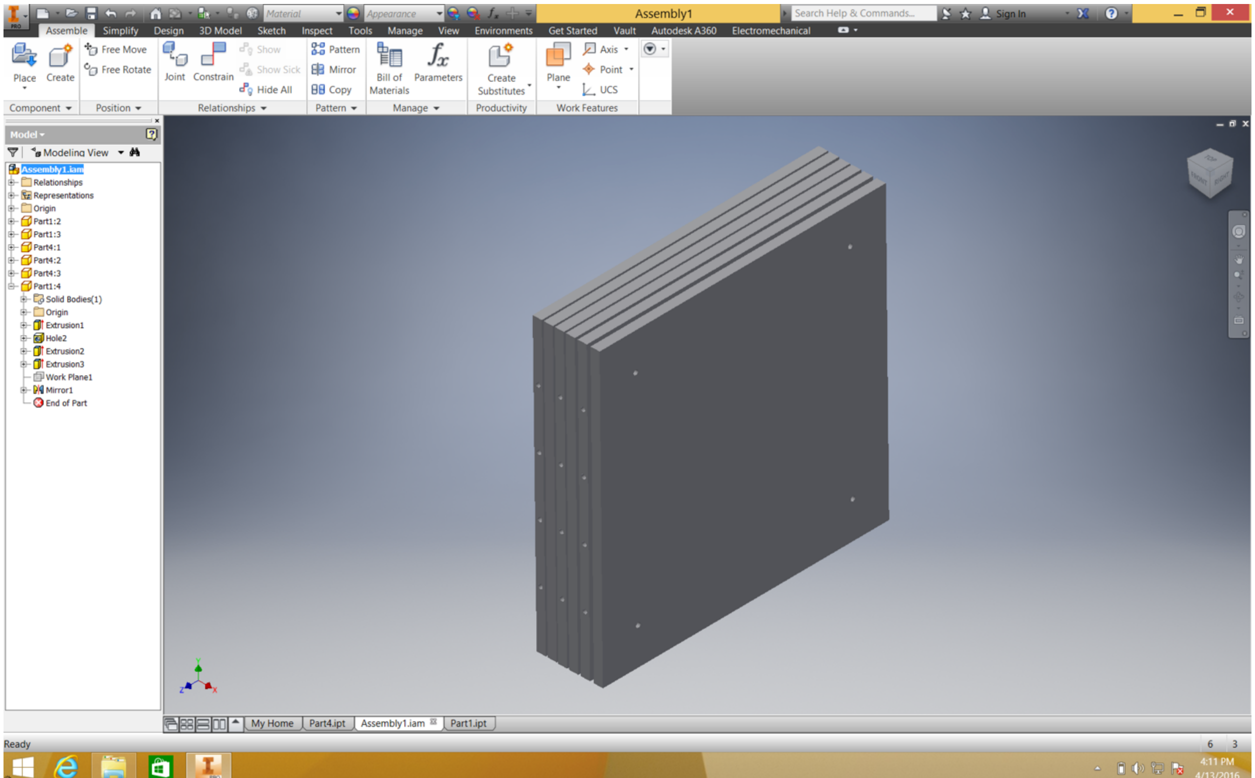


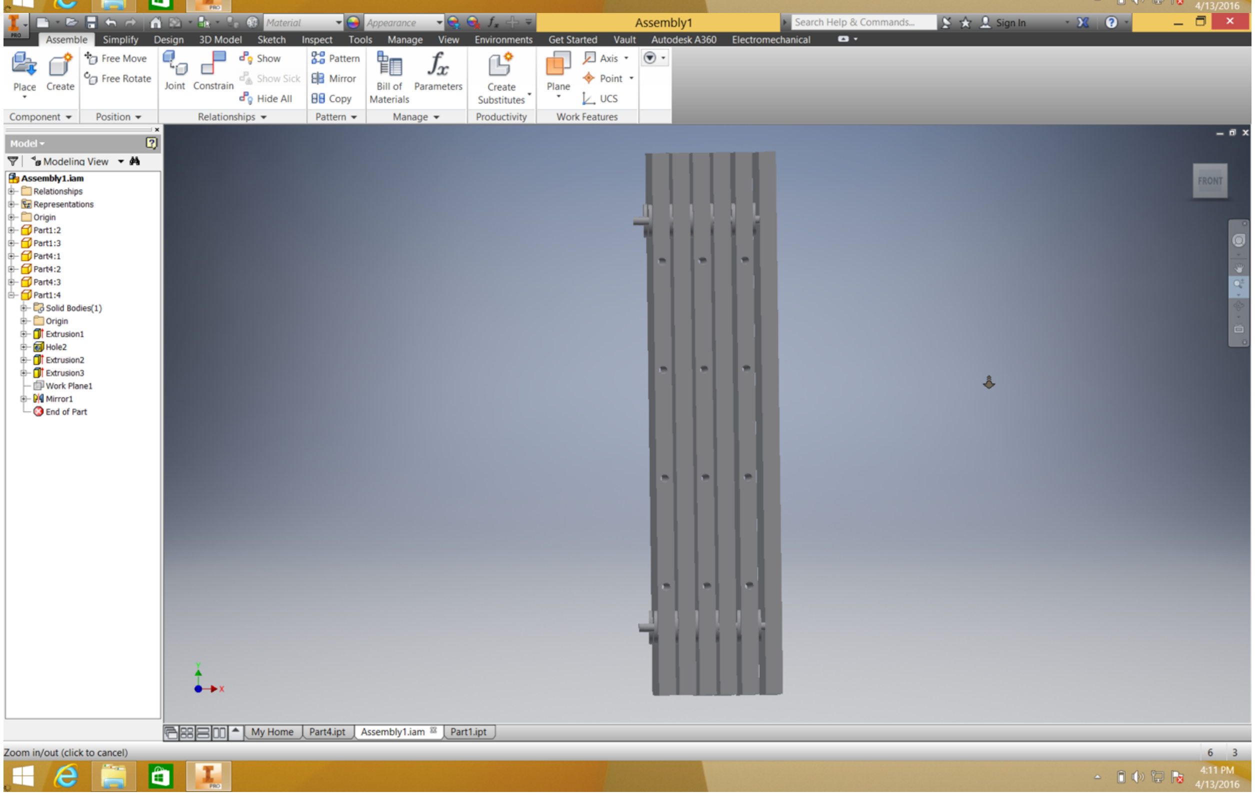












III. Discussion and Conclusion

Many iterations of the cooling systems were thought up before we came up with internal channels running in between the cells of the batteries. When the assignment was first picked up, the previous members suggested an external cooling using a single channel running serpentine on either side of the battery. Unfortunately, their design was neither thorough nor precise enough for us to use, so it was scraped. The first design we had for an internal cooling system was to run an inert coolant through porous electrodes. The idea was to take advantage of phase change like Al Cell, to help keep the electrodes of the battery, but there was not enough data about what whether or not the battery would still function if the electrodes were porous and had a coolant run through them.
The next idea we had for the design was to have the outer casing of the battery to be stripped and have the inner layers be entirely submerged in a vat as a coolant flows in between the layers, not unlike how Tesla externally cools its batteries. This way of cooling would still use phase change. Originally, this was thought to be a good idea until the calculations were made, revealing that a huge surface area of the battery layers were needed in order to take away all the heat that was generated. After researching more options, we decided on our current design: to have multiple channels run in between the layers of the battery.

We believe that our design for internally cooling lithium ion batteries is the most efficient one for eliminating the heat generated when the battery is charged at the rate of 4C. Our design is aimed at keeping the battery no higher than 45 degrees Celsius as it charges as spatially and functionally efficient as possible. In theory, the channels should take out all the heat generated in the battery without sacrificing the performance of the battery.
With all our work done this semester, there is still more to be done for this project. The theory and equations have all been figured out, so the next main objective is to create a functioning prototype. To achieve this goal, more research needs to be done on lithium ion batteries, specifically how to open and alter the batteries without ruining the battery. It will take quite some time and resources, but we believe that our research will be the foundation for internally cooled lithium ion batteries.

References:

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Appendix I: Matlab code

```
clc
clear all
%Battery Coolness
%Calculating The Heat Generated from irreversible process

%Resistivity Range in mOhms for a 3.6V (Our battery is 3.7)
R = linspace(75,500);
% 16Ah is the battery, at 1 C
% C-rate = Current/Capacity
% 64A*(1/4)h* 4C = Current = 48 Amps
I = 64;
%Equation for Qir in mWatts
Qir= I^2.*R;
% Qir1 in Watts
Qir1 = Qir*10^-3
subplot(3,1,1)
plot(Qir,R,'r')
xlabel('Qir: Heat Generated from Qirr process')
ylabel('Range of Internal Resistivity')
grid on


%Current VS Time.
% Capacity in Amp hour
Cap = 1.6;
% C rate
C = I/(Cap*60); %=0.5,
%CST current till half state of charge, assuming full SOC at 15mins
%Time in mins, Current in Amps
t1 = linspace(0,9,200);
I1 = 48.000123;

%Current decreasing from
t2 = linspace(9,15,200);
I2 = 48+(1./exp(t2));

subplot(3,1,2)
plot(t1,I1,'r',t2,I2,'b')
xlabel('time')
ylabel('Current')

%Cooling

%mass flow rate  m in kg/s
%Cp = J/kg*K
%Delta T is 26?
Cp = 1000;
m = Qir1/(Cp*26)
%diameter 5 mm
d = 5;
A = pi*(5^2)/4;
%density in kg/l
ro = 1.7;
%Volumetric Flow rate  in l/s
Vdot = m/ro
```

```
%Velocity in m/s
v = (Vdot*10^6/A)/1000

subplot(3,1,3)
plot(Qir1,v)
xlabel('Q generated')
ylabel('Velocity of Fluid')
```