POLITECNICO DI TORINO

Dipartimento di Ingegneria Meccanica e Aerospaziale
Laurea Magistrale Ingegneria dell'autoveicolo

Thermal management of an ultrafast wireless power transfer system for electric vehicles

Candidate: Supervisor:

Xu Haoli Prof.Paolo Guglielmi

Student ID:233213

Abstract

The project is emphasized on the thermal management of Electric vehicle relevant to the ultra-fast charging in a static state.

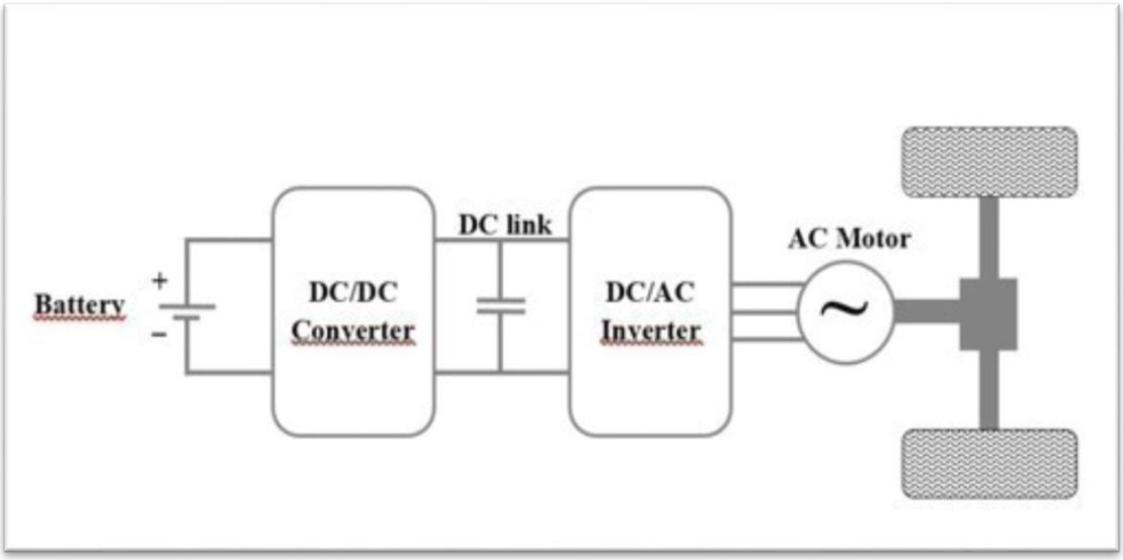
The charging power is 100KW, and the loss energy in the process converted into heat. A cooling system is required to dissipate the heat produced during the charging process.

In the project, the thermal model is established, also several simulations are mandatory to make the conclusion. The process involved the design the 3D model and drawing, simulation of the designed model and intergraded with the vehicle cooling system.

Software Solidworks and SimulationX are specially utilized for the purpose. The Solidworks is responsible for drawing the model and simulating the cooling process. The Simulation X is calculated and plots the states in charging process.

Preface

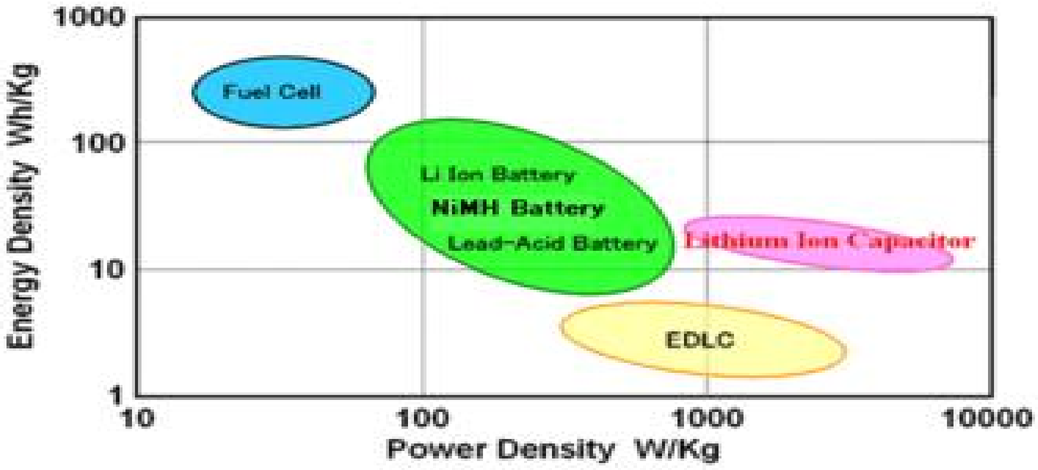
Nowadays, the vehicle is electrifying and intelligent. The electrical energy for propulsion shall ascend the ownership in the global market. Comparison with the traditional combustion engine, the electrical motor possesses the merit on the excellent efficiency, carbon emission, reduced volume, lighter weight and less noise, besides, it simplifies the transmission system likewise. All the virtues pander to the trend of 'Green Life' and the sustainable strategy, especially in the urban section.
The layout of Electric Vehicle is not complicated. Basically, its power supplied from three sub-systems: the traction system, the power storage system and invert system. The traction system is mainly consisted of electronic motor (three-phase induction motor) and gear box; the storage system depends on battery and the invert system is electronic power invert.



Power modules for Electric Vehicle

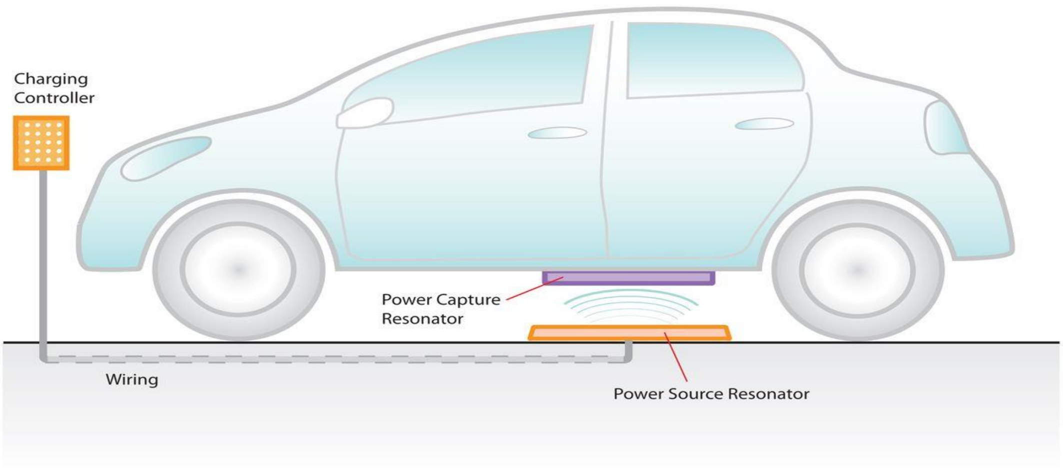
From the above figure, It can be known that the battery render the electronic energy with direct current (DC). Obviously, the structure can be simplified if equipped the DC motor. The reason for substituting the DC motor to three phase alternatives current (AC) motor is the durability and complexity. Although the former's mechanism is relative straightforward, the structure is more complicated in reality. An additional circuit for excitation is necessary and the brush also wears readily. Inversely, the latter's method is not easily acceptable (three phase current induces a rotational magnetic field, consequently, a current in rotator will be produced, then the rotator starts to move due to Lorentz Force), but, frankly, the structure is simple, and the durability is superior than the former (No extra circuit for excitation and brushless).
Whereas, the batteries' specific power and energy contrary (according to the Ragone plot), which reveal there is no likelihood to produce a battery with excellent performance on both quantities all together. Besides, the specific energy of the battery obviously is less than the fuel, in other word, with the equivalent weight, the

traditional fuel is able to sail longer distance. Moreover, the charging time restricts the battery prevailing. The recharging demands a longer period than fuel filling that confine the efficiency when the extended trip requested. Also, the charging process rely on the Electric Vehicle Supply Equipment(EVSE), however, the sorts of facilities are dearth and request additional space, which make the driver envisage the status that is inconvenient in seeking a EVSE when it is mandatory.



Ragone plot

In order to tackle the issue of the distance, current solution is serial and parallel the batteries'' modules and the utilization of the range extender. Nevertheless, not only it augments the volume and weight of the automotive, but triggers several knots to thermal management. As for the charging time, to approach the petrol car's fuel filling time, the ultrafast wireless charging is researched and developed. Basically, it implements the methodology of the electromagnetic induction, burying coils beneath the ground as the source, and the coil installed in the automotive acting as a part of receive. In static situation, when current flow though the source coil, the coil in the vehicle will also react and generate a current to charge the battery. This process is designed to fulfill in five minutes, with a powerful current induced in the coil. As a consequence, the wireless power transfer (WPT) system is required to undertake the intensive current to ensure the security as well as the cooling is essential.



Schema of wires charging

Seemingly, The WPT system assists the electricity to be a more sufficient and environmental resource to supersede the traditional fuel. Plus, it is an accessible solution to downsize the battery because the WPT system can additionally actualize the dynamic charging. Contrast with the traditional cable charging equipment, the WPT device has the advantage in less dust and wear of contact. Under these conditions, the cost on the maintenance is relative low. In addition, the WPT device is in a position of stabilization in severe weather condition and environment.

For this reason, to accomplish the application, the WTP system is supposed to be strictly designed. Virtually, when the coil in the vehicle matches, the strong current is going to flow though the wire. Definitely the wire, battery and the coil must be fabricated to stand it. However, the heat engendered due to Joule effect remains inside these systems. With time goes by, the heat accumulates and transfer which is detrimental to the vehicle, melting the wire, even evoking the fire.

The thermal management of the vehicle must take into account this phenomenon and solve the problem to guarantee the entire system operating in a secure situation. In previous vehicle, the thermal management are mainly responsible for the cabin (human), the traction and battery system. Now, the charging system will interact with them.

Basis of the current researches, the WPT is capable of realizing two different ways of charging: dynamic charging and static charging. The former supplies the current to vehicle during the movement, and the latter render the energy when car parking. Certainly, there is a discrepancy between them, the reason of that is the circumstance.

The dynamic charging generally adopts the air cooling, the reason of that, when the vehicle is driving along the road with a serial of coils hidden under the ground, the air flow is fast, and the heat stored inside the WPT system is released to the air. In the current product of dynamic charging, in particular, OLEV, TBD, WiT-3300, almost all of them take the air as the coolant media and the power input is relative low.

Instead, the coolant for static charging is designate as the water, due to the high specific heat whose property is ideal for cooling. Particularly, the air impact will be neglected at the static condition. The power input in this case will culminate in 100KW. It is believed that the cooling for the stationary WPT system is a strait task. There are two scenarios proposed in handling the mission. Since water is a laudable cooling agent, one of the plans is combining the cooling system already installed in the Electric Vehicle (EV) to the WPT system, in other words, they will share the common cooling system. This technique is aimed to facilitate the complexity of the vehicle and the cost. The flaw is the heat removed from the WPT system will no doubly rises the water temperature. It's known to all that the battery and the traction system are necessary to be cooled in the normal operation. If the battery runs in a high temperature condition, it will accelerate the rate of aging which is detrimental to the life of the battery, even extremely, the battery might be ignited. The accumulated heat in the electric motor will decrease its efficiency as well and lead to a negative impact on the performance of the vehicle. The other, depend on the first solution, if take into account the WPT system, the rest part will suffer serious influence, then the additional cooling system are required. Unfortunately, the investment of system scales up and the layout of the vehicle are compulsory to be adjusted. In one word, the issue can be concluded in several ways: the design of the cooling system of the WPT; combine the EV existing cooling system with WPT or a special design for WPT.

Apparently, the idea solution is Integrate the existing cooling in the automobile with the WPT system. It can reduce the cost and decrease the complexity of the car. Therefore, furthermore research and simulation will be executed in order to discover optimize scheme.

Contents

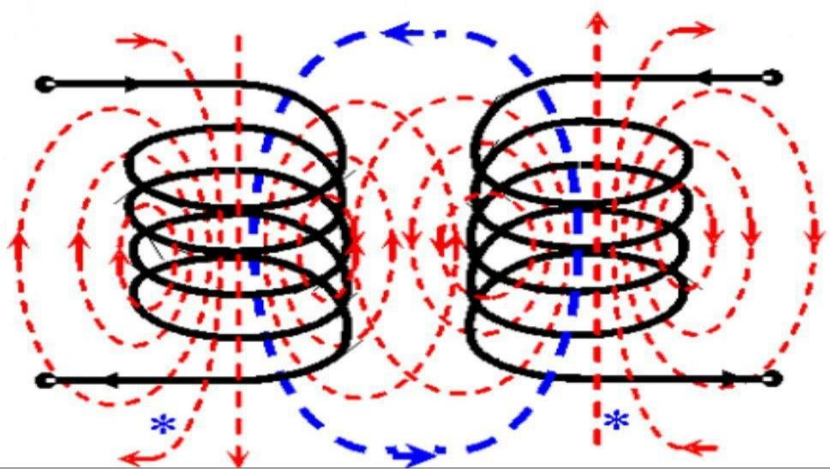
Chapter 1

Basic Theory background

For design the system, the principle applied will be introduced. Two mythologies are considered. One of them is electrical which indicates the charging system operation, and the other illustrates three basic three models that depict the thermal issue.

1.1 Electrical theory

Generally speaking, The WPT system wields the principle of electromagnetic induction.



Electromagnetic induction

The left coil as the source induces a magnetic field and the right one as the receiver. In automotive, the left coil is that on the ground and the right coil load in the vehicle. When engaged, a varied current (alternative current) though one coil induces a varied magnetic field.

$$B = \frac{\mu \cdot I}{l}$$

Where,
μ is the magnetic permeability relative to material;
I is the current though the coil;
l is the length of the coil.
The formula shows the relationship of the magnetic flux density with the current and the length of the coil

When the varied magnetic flow though other coil, an induced voltage will rise to produce a magnetic in order to counteract the change. And the voltage can be roughly calculated by the following equation:

$$\varepsilon = n \cdot \frac{\Delta\varphi}{\Delta t}$$

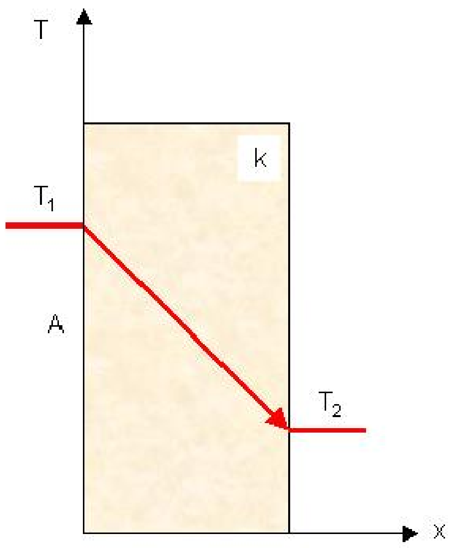
Where,
n is the number of turns in the wire coils;
φ is the magnetic flux;
t is the time.
In reality, when the current flow though the conductor, a part of the energy will change into heat. That is called Joule effect.

$$P = I^2 \cdot R$$

Where,
I is the current;
R is the resistance of the conductor.

1.2 Thermal theory

Conduction
Due to a temperature gradient in the medium (solid or fluid in static state), the heat transfer occurs within the medium are called Conduction.



Conduction

Fourier's law describes that given a one-dimensional plane, the rate of heat transfer per unit area perpendicular to the heat transfer direction (the direction of temperature declining) is proportional to the temperature gradient.

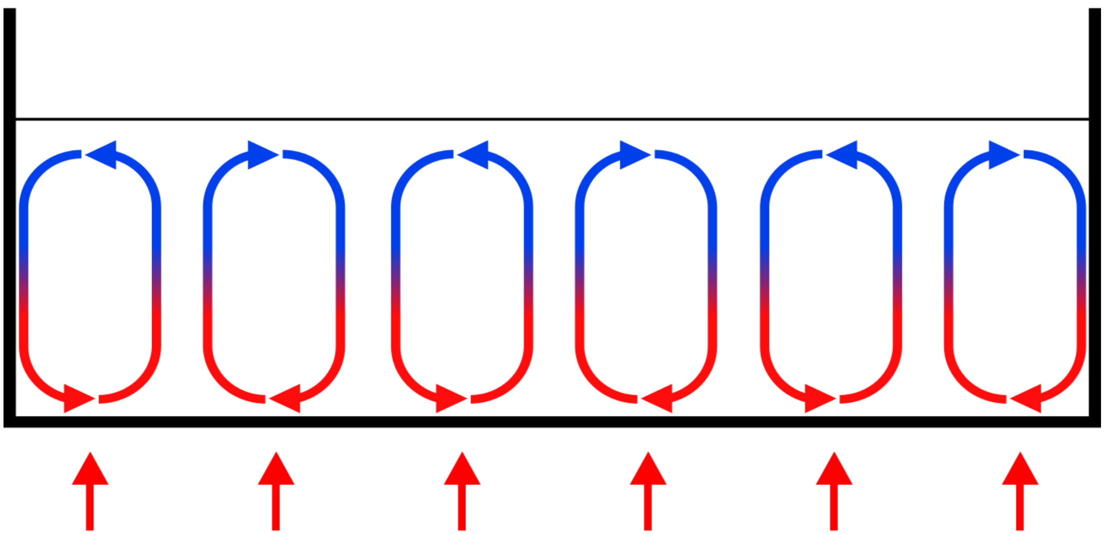
$$\dot{q} = \frac{\dot{Q}}{A} = -K \cdot \frac{dT}{dx}$$

Where,
K is the thermal conductivity of the material;
T is the temperature;
x means the direction of heat transfer.
In addition, the sign is relative to direction of temperature decreasing.
In steady state, if the distribution is linear, the equation can be re-written

$$q_x = K \cdot A \frac{T_1 - T_2}{L}$$

Where,
K is the thermal conductivity of the material;
A is the area perpendicular to the heat flow;
L is the thickness if the wall
T_1 is the higher temperature
T_2 is the lower temperature

Convection
The heat transfer happens between a fluid flow and solid surface due to the discrepancy of temperature and relative motion.
This kind of transfer can be either from fluid to the solid or solid to fluid, it depends on which own the higher temperature.



Convection

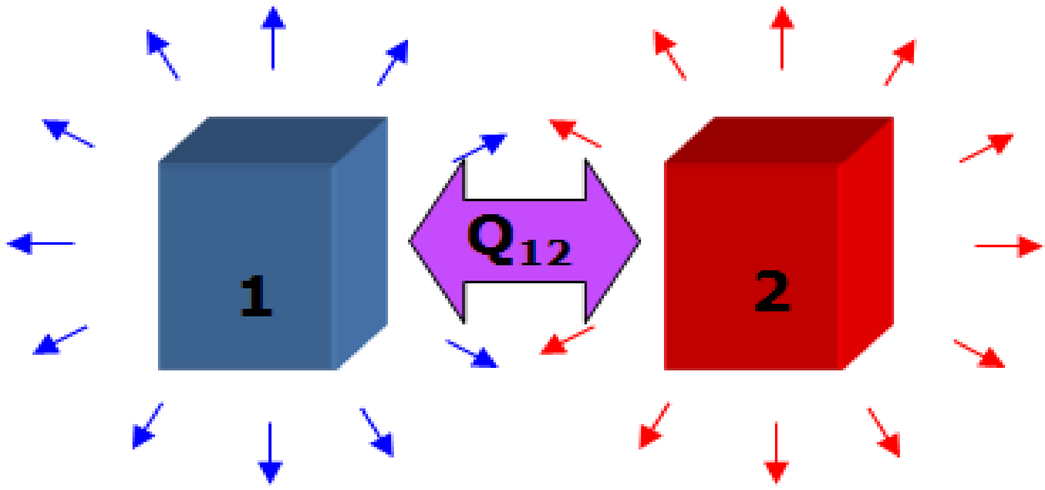
Newton's law indicates the heat transfer rate per unit area relative the temperature gradient.

$$\dot{q} = h \cdot (T_w - T_f)$$

Where,
h is the convective coefficient;
T_w is the temperature of the solid;
T_f is the temperature of the fluid.
If taking into account the contact area, the rate of heat transfer is obtained.

$$q = h \cdot A \cdot (T_w - T_f)$$

Radiation
The heat flow emmited from a stuff with a certain temperature is Radiation.



Radiation

Stefan-Boltzmann's law demonstrates the process, a heat flux transfer across the space from a part with temperature T_1 to the other with temperature T_2 without any absorbing material.

$$\dot{q} = \sigma \cdot (T_1^4 - T_2^4)$$

Where,
σ is Stefan-Boltzmann constant.
For real situation

$$\dot{q} = \varepsilon \cdot \sigma \cdot (T_1^4 - T_2^4)$$

Where,
ε is an emissivity factor between 0 and 1.

Chapter 2

The model of wireless power transfer system

For deeply studying the thermal question relative the wireless power transfer system, it's essential to build up a geometry model at beginning. Thereby, several mechanical constrains are able to be explored. Based on that, the details of design will be developed and the model can be drawn in the software: Solidworks.

Particularly, in the current situation, the charging process last 5 minutes and the charging power is 100Kw. Meanwhile, there is 10% of the charging power loss due to Joule effect and turn into heat (10kw of heat produced). Plus, assuming the coolant for WPT system shares the same with existing in the automobile. Thus, there are special requirements for the total system: The temperature of the battery during charging cannot be higher than 50 ℃; the WPT system's temperature should lower than 65 ℃; the coolant temperature less than 45 degree after cooled by the radiator.

2.1 Geometries and parameters of wireless power transfer system

Several parameters already known:

The container, whose shape resembles a box, the specifications are in the following:

Length: 850mm;

Width: 850mm;

Height: 75mm.

The coil, simplified by a hexagon region with three layers, releases the heat flow. The parameters are in the list:

Size: 840cm;

Aluminum layer: 0.5cm;

Ferrite layer: 1cm;

Copper and PCM (phase-change material) layer: 1.5cm (20% copper and 80% PCM).

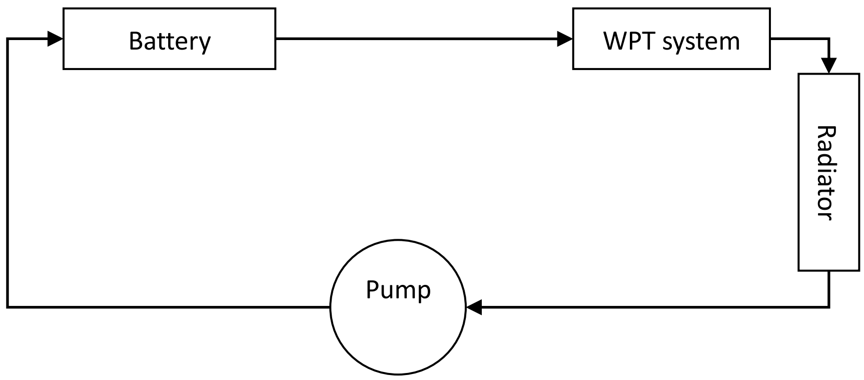
Coolant, the best choice is water, because of its excellent heat capacity. However, considering the environment condition, the additive should be used.

Composition: 50% water 50% glycol.

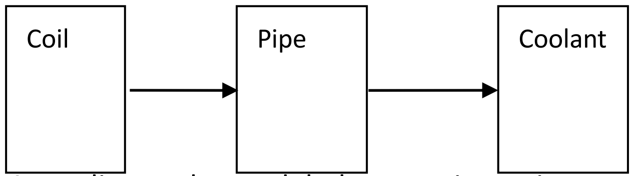
Heat capacity: 3.74 KJ/ (kg·∗ ℃)

2.2 Design the cooling system

For the cooling down the WTP system, fluid pipe can be intergraded to the system. Therefore, the modules can indicate the entire cooling system:



To ensure the temperature of WTP system satisfy the critical, the coolant temperature should be limited at a certain lever, by the way, the PCM can take half of the heat and storage it, thus, the cooling system are rarely asked to carry the rest of heat (about 5Kw).
Depending on the heat transfer theory: conduction and convection, hypothesis the flow is steady state and one-dimensional flow facilitates the calculation. A thermal model is established.



According to the model, the equation written:

$$q = K_r \cdot A \cdot (T_{wpt} - T_{coolant})$$

$$K_r = \frac{1}{\frac{L_1}{K_1} + \frac{L_2}{K_2} + \frac{1}{h}}$$

Where,
K_r is the global heat transfer coefficient;
A is the sufficient contact area;
T_{wpt} is max allowed temperature of WPT;
$T_{coolant}$ is the max temperature of the coolant.
L_1 is the thickness of the coil;
K_1 is the thermal conductivity of the coil;
L_2 is the thickness of the pipe;
K_2 is the thermal conductivity of the coil;
h is the heat transfer coefficient of the coolant.

Also, mass flow rate is obtained by the equation

$$Q = c \cdot m \cdot (T_{out} - T_{in})$$

Where,
c is the thermal capacity of the coolant;
m is the mass flow rate;

T_{out}= The outlet temperature of the coolant;
T_{in}= The inlet temperature of the coolant.

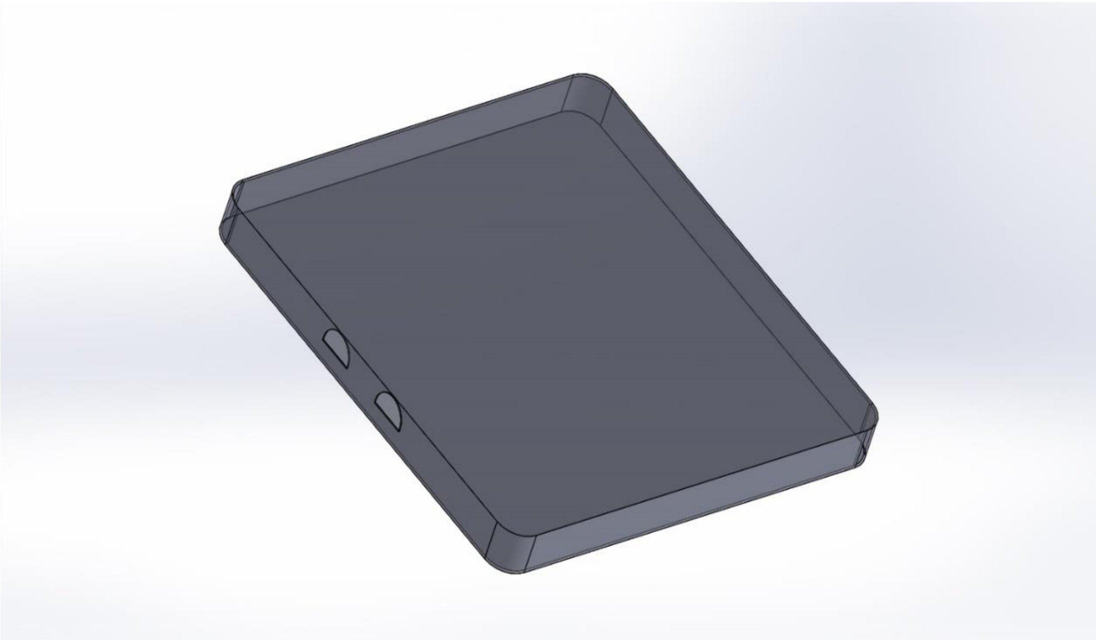
Input data:
T= 5min;
Q= 5KW;
Size of container: 85cm∗85cm∗7.5cm;
Total length of coil: 3cm
Target temperature of WTP system= 65℃ ±5℃;
Target temperature of battery system= 50℃ ±5℃.

Output data:
Qdisspate≥5KW;
Area≥300000mm^2;
Tcoolant =40℃ to 45℃;
Mass flow rate of the coolant≥ 0.2586 kg/s.

Hence, as a results of the data, Set the mass flow rate as 0.4kg/s, the pipe contacting area is 318900mm^2, and the coolant temperature is 40℃, and they shall be utilized as the parameters for simulation.

2.3 Model drawing

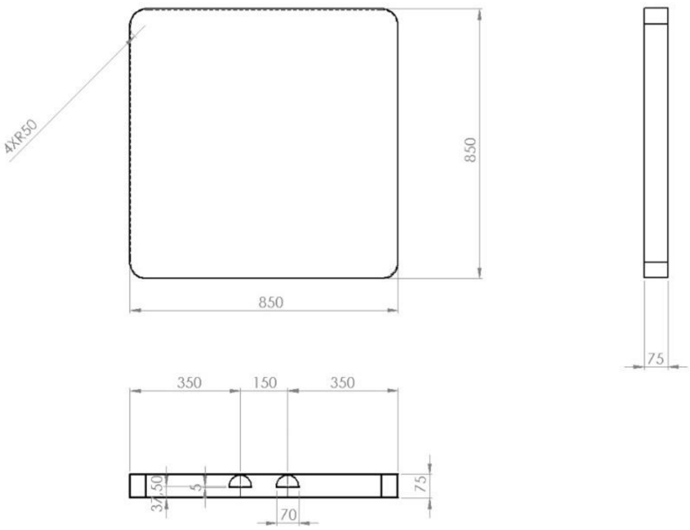
After the design, the model of container can be easily sketched in Solidworks. The container functions as a cover to the coil and the cooling system. However, the influence of the box can be neglected when the car remains static. The photograph of the model in following:



Model of the box

The material for the box might be plastic or iron. The plastic material is less weight, on the contrast, the iron would be more heaved but hard. Besides, two holes are drilled for the pipe.

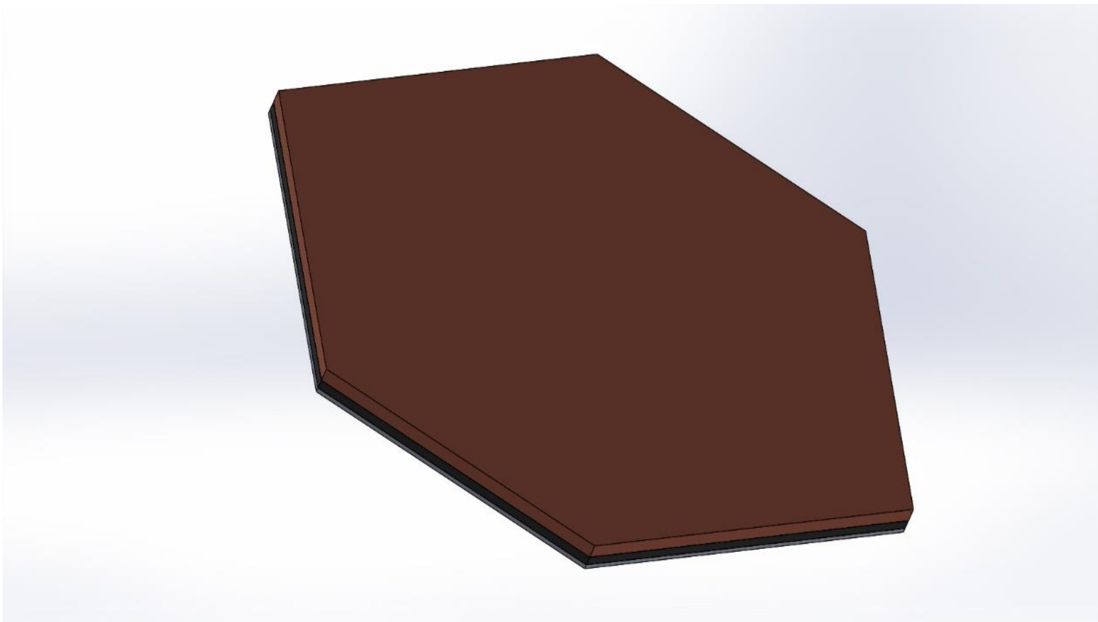
It is required to have enough cavities for the cooling pipe and not to interface the layout of the vehicle.



Specific dimension of the box

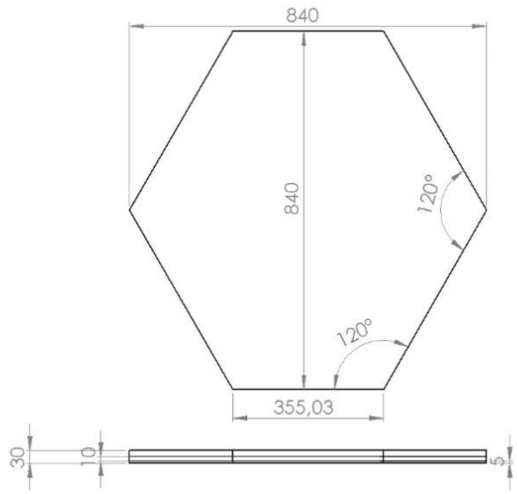
From the drawing sketch, its dimension is obvious. The length and wide are both 850 mm, the thickness of the wall is 5mm, and the height are restrained by the vehicle, therefore it is restricted in 75mm.

As for the coil, in the model is simply, the reason is for the thermal analysis, the internal structural can be neglected, barely introduced the material affect.



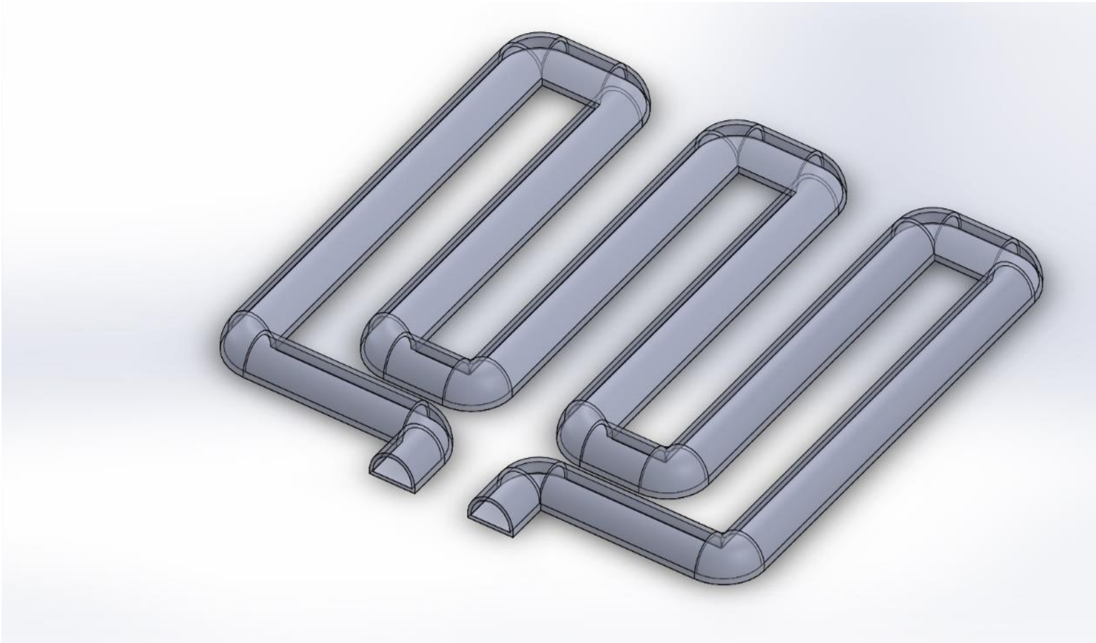
Coil

In the figure, three pieces of hexagon sheets assemble it. The Aluminum layer is on the bottom whose thickness is 0.5cm. In the middle, the ferrite layer is 1 cm. The copper and PCM layer is on the top, which thickness is treble than the Aluminum layer, the total height is 3cm.
In detail, for a better way to understand the model, the 2D drawing of the hexagon is attached in following:



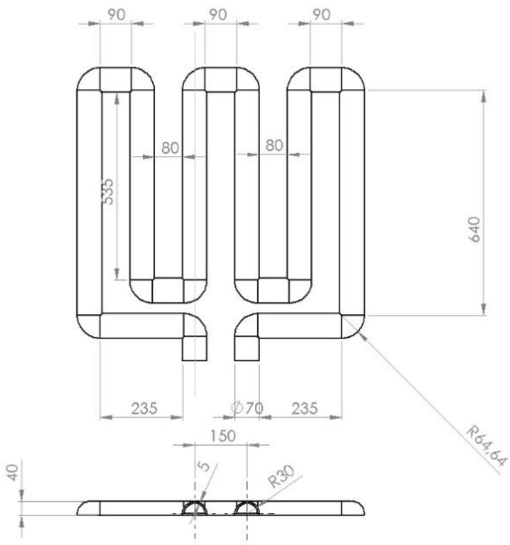
2D drawing of the coil

The pipe for cooling the WPT system is conceived relied on the results above. Certainly, the pipe plays an essential role in the system. The coolant inside the pipe should absorb the heat and release to the circumstance, and the function of the pipe not only is a carrier of the coolant, but also is a conductor for the heat transfer. To achieve a superior cooling effect, the arrangement of the pipe is an extremely factors. In principal, increase the contact area is benefit in heat transfer, and more and more turns of the pipe are appreciated. Nevertheless, the dimension of the box limits the size.



Model of pipe

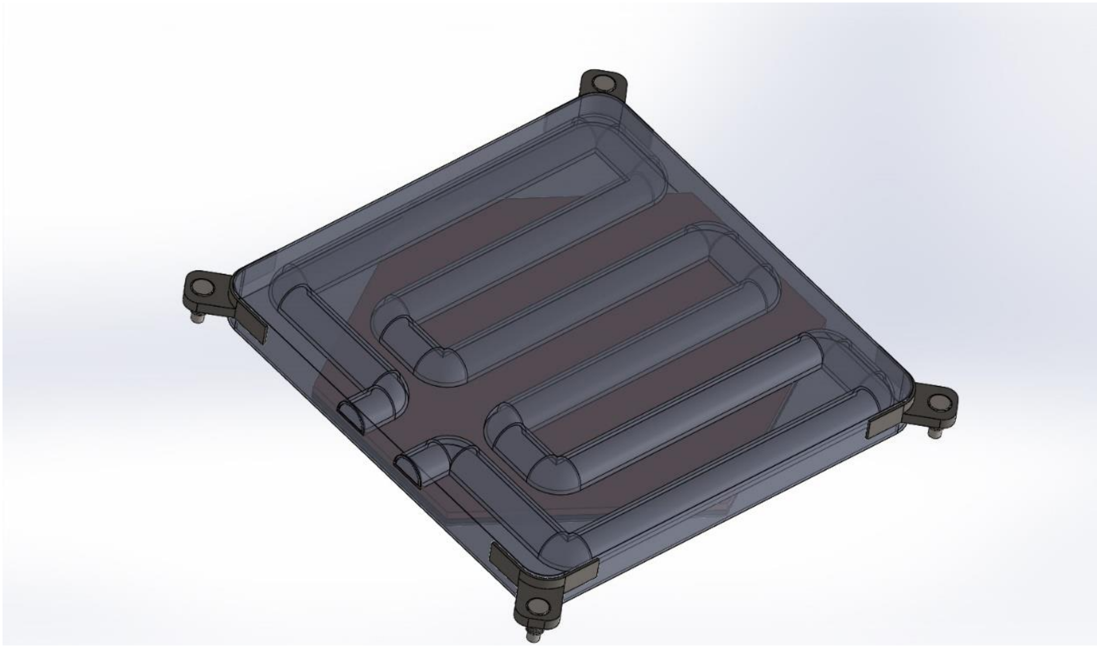
The cross section's shape of the tube is a half circle and material selected as aluminum for its good thermal conductivity. A dimensional sketch is reported likewise:



Dimensional sketch of pipe

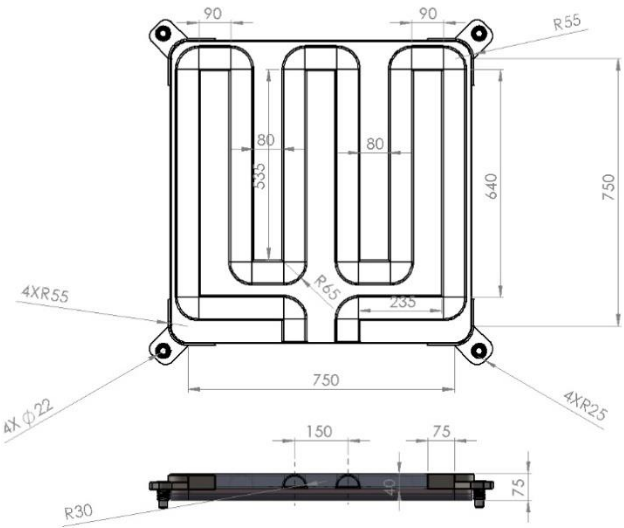
Due to constrain of the box's size and the coil, the maximum height of the tube is 40 mm. The size of the holes is both 30mm. one is the inlet port and the other is outlet port. From these parameters, the area of the pipe is approximately 318900mm^2, and the tube length is 5130mm.
At the end, all of these components are supposed to assemble to be the WPT system. The system contains three mainly parts: the container, the coil and the pipe.
Consider the box should be fixed on the vehicle, the fixture should be added up, plus,

taking into account vibration during the driving process, a spring should be utilized to absorb the impact.



The wireless power transfer system

In the assembly, the copper and PCM layer is contacting with the pipe, because the thermal conductivity of the copper is superior to other material.



The technique drawing

Combine the two graph, the pipe is nearly covered the box and stick on the coil in order to effectively cool down the coil.

Chapter 3

Simulation of the WTP

To verify and check design for the system is sufficient or not, simulation for the cooling process is mandatory. In the fact that the results' accuracy is not high, the software Solidworks is employed. Differ from the drawing function; the module of flow simulation is the best option to simulate the flow process.

3.1 The settings for simulation

Before the simulation, there are several parameters are necessary to be defined and remain constant.
General setting:
The material: expect the pipe and coil, the rest are default as stainless steel;
The fluid: water;
Simulation time: 350s (ECU calculation time as the charging time);
Lid: if open port existing, it required to be closed by lid.

Simulation setting:
Boundary condition: the left port as inlet defines as the mass flow and the right as b outlet defines as the static pressure port (to ensure the simulation run successfully)
Volume heat source: the coil;
Volume goal: temperature of coil (solid temperature); temperature of the pipe (solid temperature);
Surface goal: heat transfer of coil's surface; heat flux of the coil's surface;
Thermal transfer type: internal type (only consider the heat transfer inside the system);
Results: temperature of the coil; temperature of the pipe; Surface heat flux of the coil; coolant temperature.

3.2 Simulation results in different cases

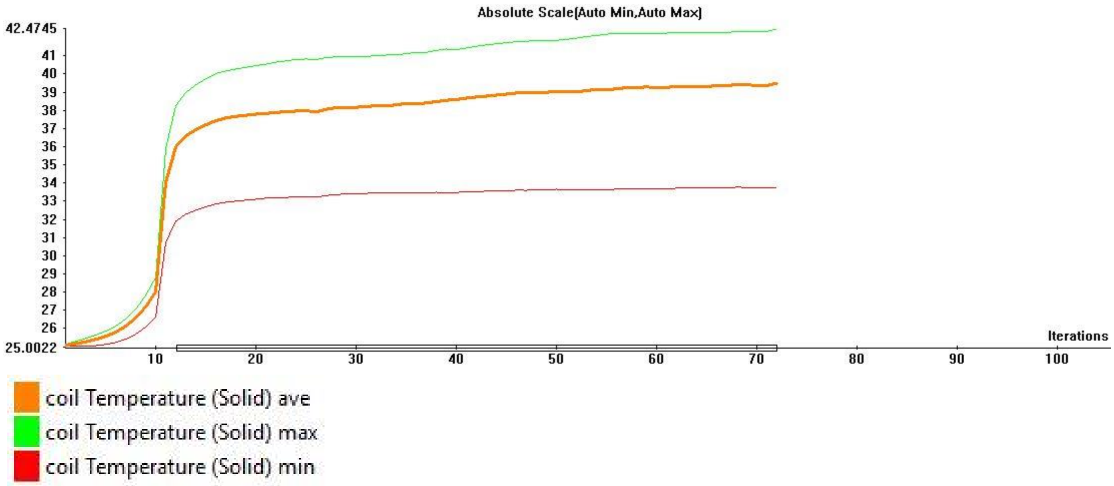
The coil can be regarded as a heat source, thanks to the PCM material (storage the thermal power),which save half of the total heat flow, the thermal flow released the the cooling system declines to 5 KW.

There are several different conditions simulated in following:
Case 1
In the ordinary environment condition, general set the temperature in the range of 20℃ -25℃ and the pressure are fixed at 1atm. The solid part should not less than the environment temperature, and the default value for the environment is 25℃.

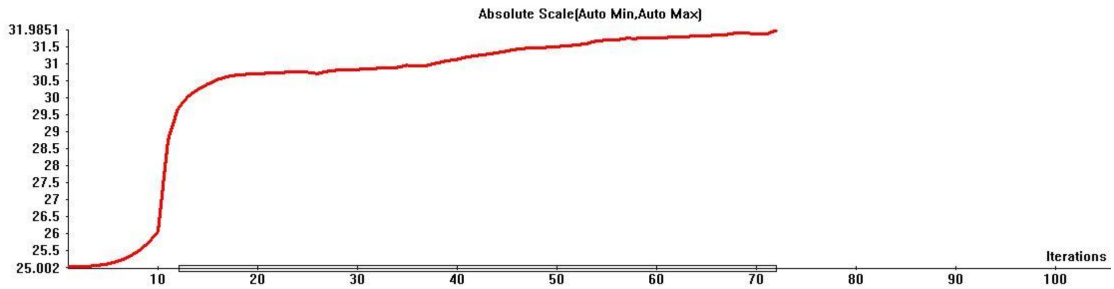
Input parameters:

Inital condition for solid:Temperature=25℃;
Inital condition for fluid:Temperature=25℃;
Outlet boundary condition: Presure=1atm; Temperature= 30℃;
Inlet flow rate=0.4kg/s;
Inlet flow speed: 1m/s (y-axis);
The power of heat: P=5000 W.

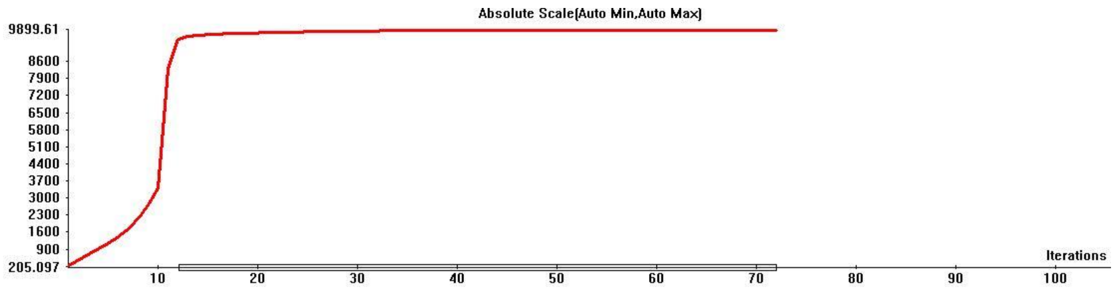
Output linear graph:



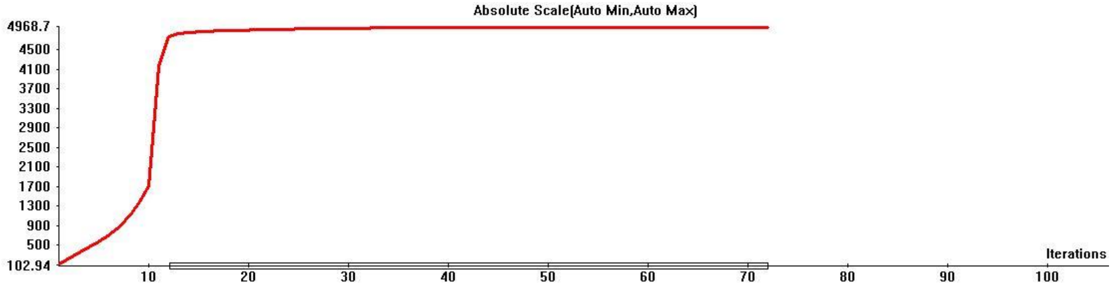
Temperature of the coil



Pipe temperature (average)



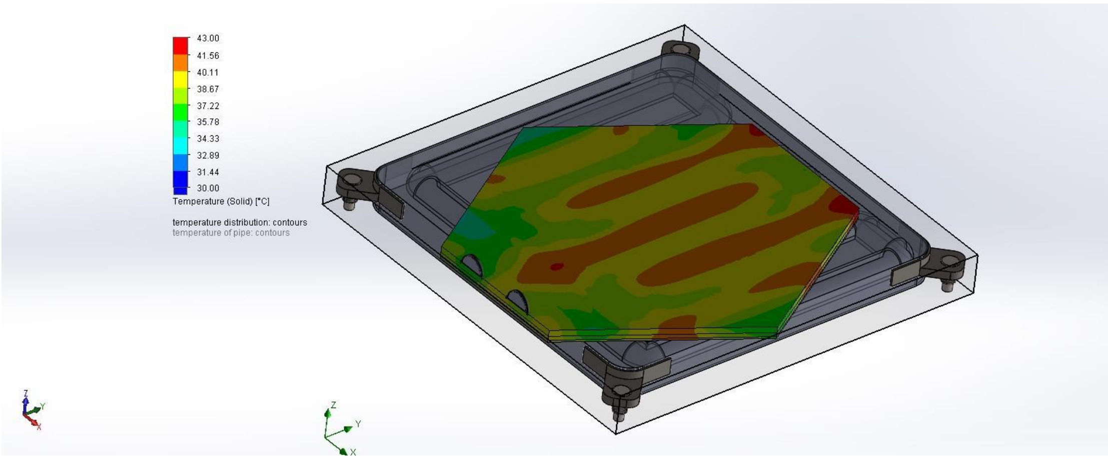
Surface heat flux (average)



Heat transfer rate (average)

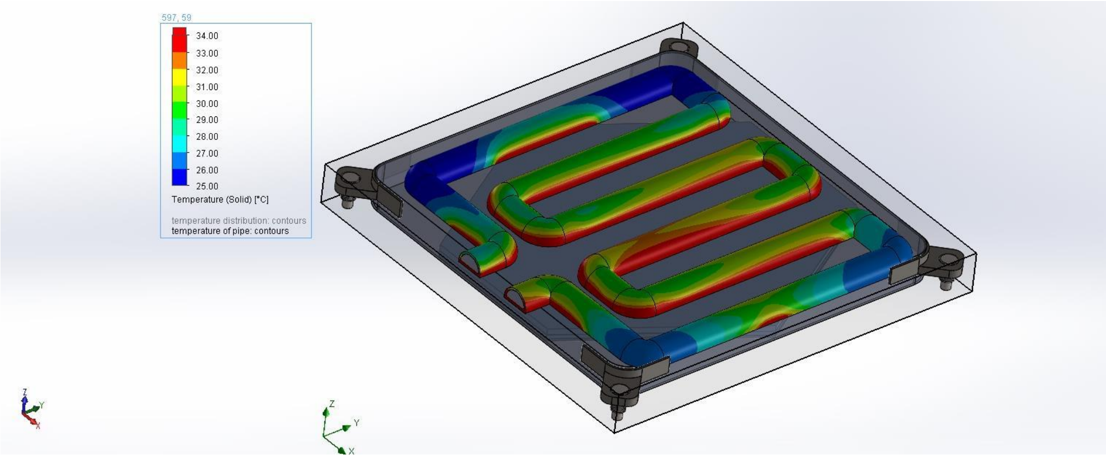
From four linear graphs from the program solver, it is obvious all of them share the same trend, starting rising at the beginning, and then keep floating. In detail, in the diagram Temperature of the coil, the culminate value is approximately 42.5℃, which indicates that the maximum temperature of the coil is acceptable. The temper of the pipe is rising from the initial temperature 25℃ up to nearly 32℃. Moreover, the Surface heat flux remains stable at the 9900 W/m^2, this value is obtained from the calculation, which is the power of heat divided the area of the coil (0.5m^2). As for the heat transfer, it is lower at beginning because the discrepancy of temperature is very low, and it is little heat transfer occurring.

Results in simulated diagram:



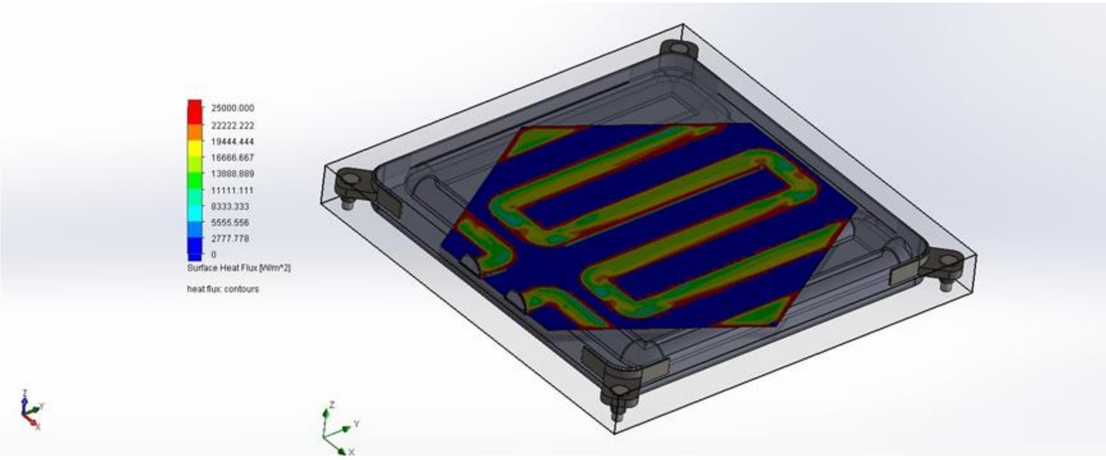
Temperature distribution of the coil

The detail of the distribution of the coil's temperature is presented. In the figure, the region in red color stands for the high temperature region, and the average value of them is about 40℃. The green region means that the temperature is relative lower.



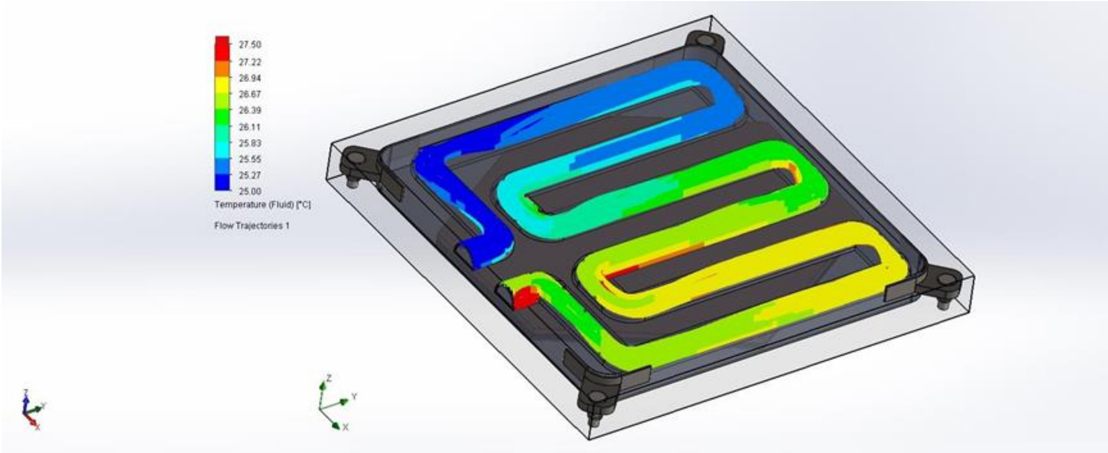
Temperature distribution of the pipe

The pipe temperature distribution illustrates the high temperature region (red color) is the area the pipe and coil contacting with each other. The non-contact surface the temperature is low, which is coincident with the common knowledge.



The heat flux distribution

The scheme demonstrates that the heat flux is concentrated on the contacting area between pipe and the surface of the coil. It means that almost of the heat is taken away though the region.



Coolant temperature variation

The coolant (water) is flow into the system from the left port in the picture, and flow out though the right port. The temperature is varied when coolant flow though the pipe, and the temperature is rising from the inlet port to outlet port.

Case 2

Particularly, a sever condition should be considered. The heating area is the entire surface of bottom of the container instead of the hexagon region; consequently, the heat power should be change to a higher value. Besides, the rest setting is the same with the former case. In the ordinary environment, the temperature is 25℃.

Input parameters:

Inital condition for solid:Temperature=25℃;

Inital condition for fulid:Temperature=25℃;

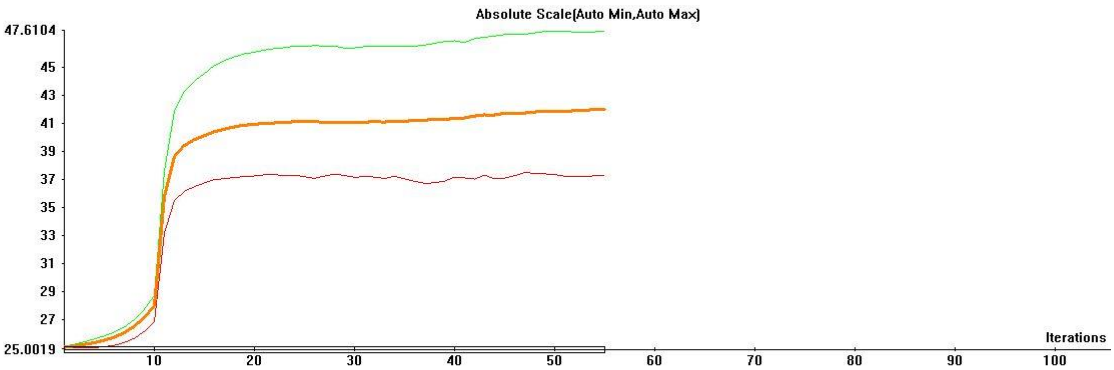
Outlet boundary condition: Presure=1atm; Temperature= 30℃;

Inlet flow rate=0.4kg/s;

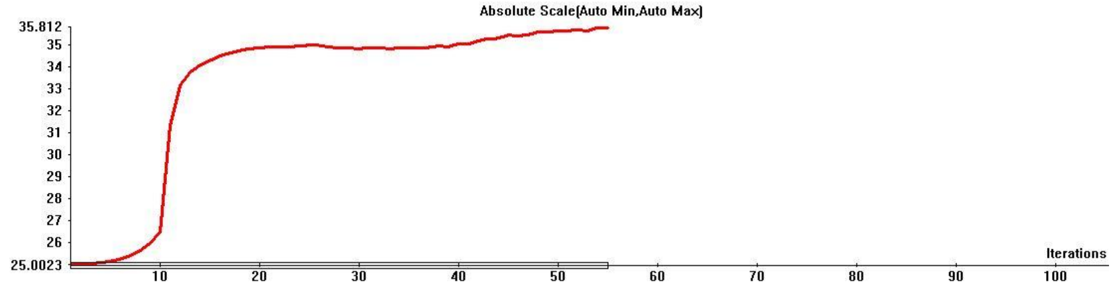
Inlet flow speed: 1m/s (y-axis);

The power of heat: P=8500W (calculated from the Surface heat flux (case 1) multiplying the current area (850mm*850mm)).

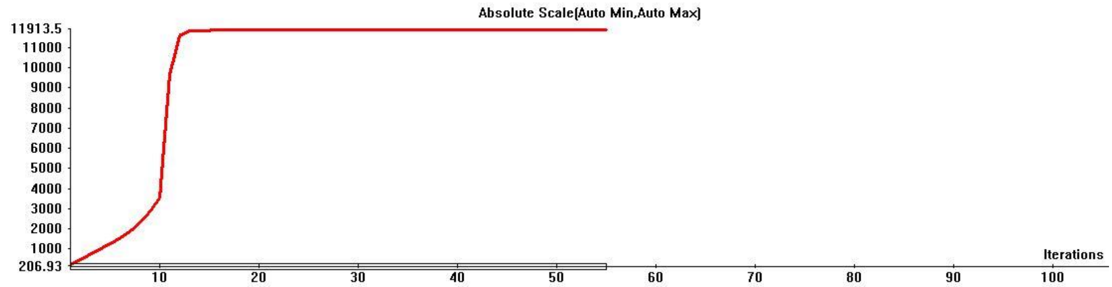
Output linear graph:



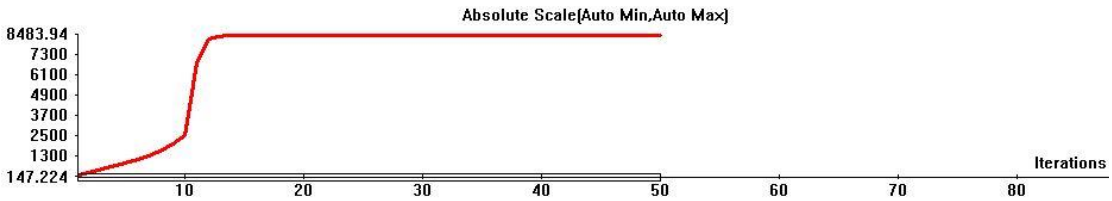
Temperature of the coil



Pipe temperature (average)



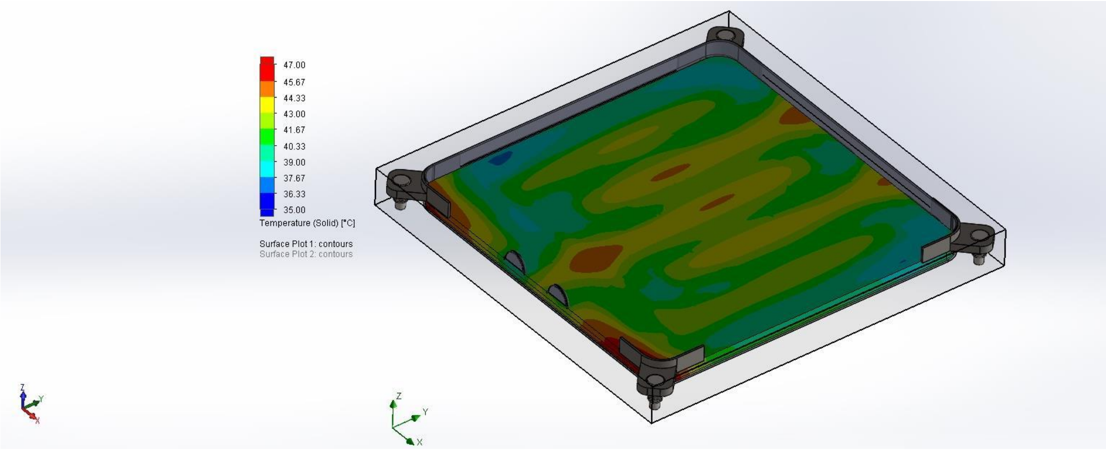
Surface heat flux of the coil (average)



Heat transfer rate of the coil (average)

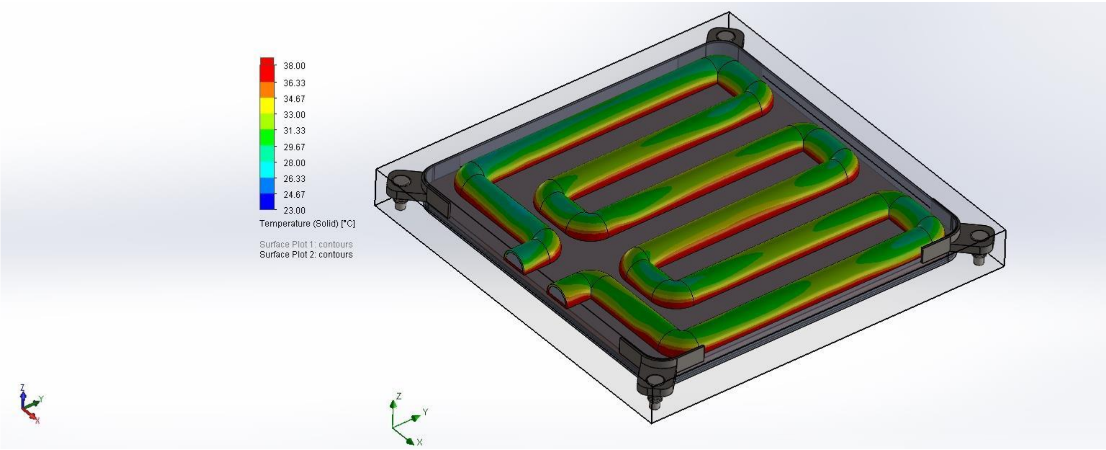
Apparently, the tendency resembles the case 1, but the value is higher. Particularly, the maximum temperature of the coil is 47.6104℃, and the pipe is warmer up to 35.8°C. In addition, because the temperature stabilizes, the heat transfer rate should correspond to the power of heat which is estimated 8.5KW .The heat flux is also increased due to some tolerance in calculation.

Results in simulated diagram:



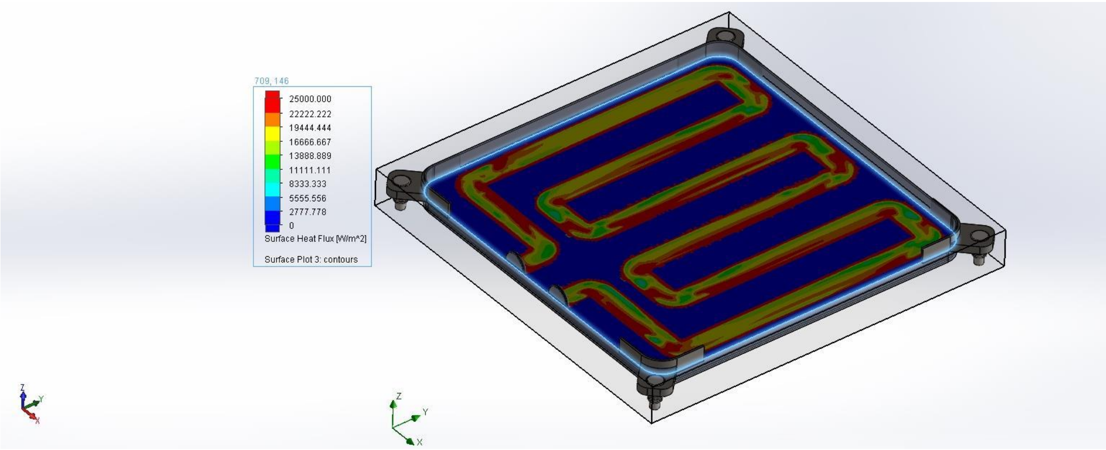
Temperature distribution of the coil

The temperature's distribution of the heat source also alters. The average temperature increased and the high temperature region has changed its location.



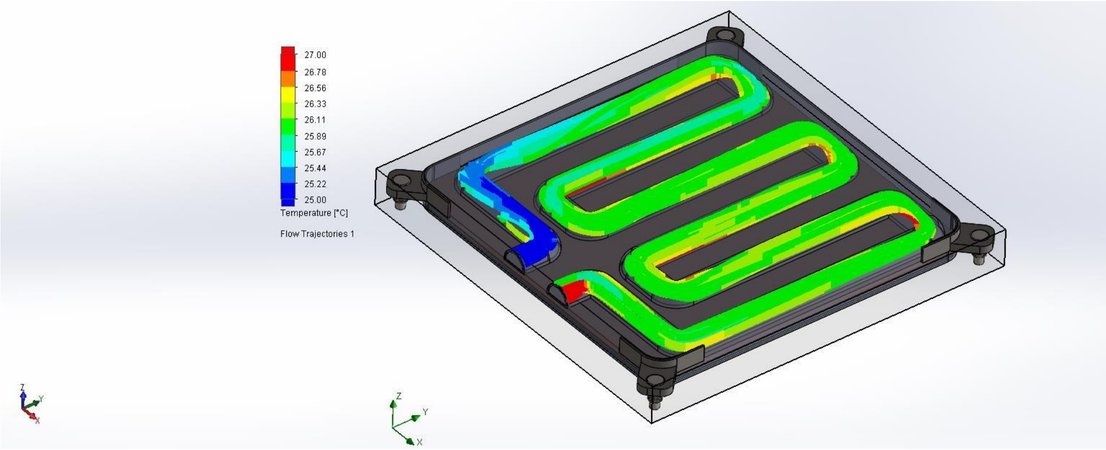
Temperature distribution of the pipe

The temperature distribution of the pipe is more uniform than before, the reason is that the contact area is extend. The high temperature area is concentrated on the toughing area.



The heat flux distribution

It reflects the path of the coolant and pipe, and the number can be estimated by power of the heat divided the area of the pipe.



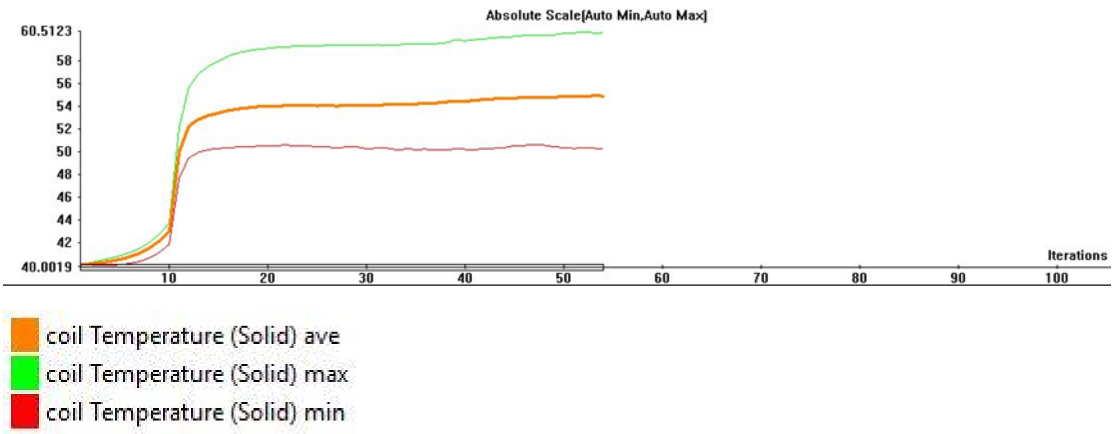
Coolant temperature variation

The coolant temperature is more homogenous. In the inlet port, the temperature is low, yet, with the fluid filling the pipe, the temperature goes up because the heat transfer from the coil penetrates into the water.

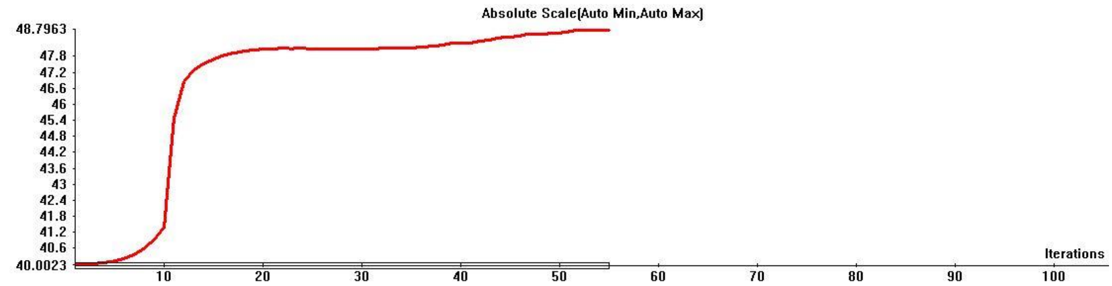
Case 3
In previous test, the environment weather setting at 25℃ and the results is in the target range (less than 65℃). Considering the weather is hot, for instance, in the summer, another simulation is supposed to run to know the impact. In this case, the temperature of circumstance, solid as well as the fluid starts at 40℃, which is the designed temperature for coolant. Plus, the heat dissipated area is the sever one (the same with case 2), and the rest parameter is required to be the same.

Input parameters:
Inital condition for solid:Temperature=40℃;
Inital condition for fluid:Temperature=40℃;
Outlet boundary condition: Presure=1atm; Temperature= 45℃;
Inlet flow rate=0.4kg/s;
Inlet flow speed: 1m/s (y-axis);
The power of heat: P=8500 W.

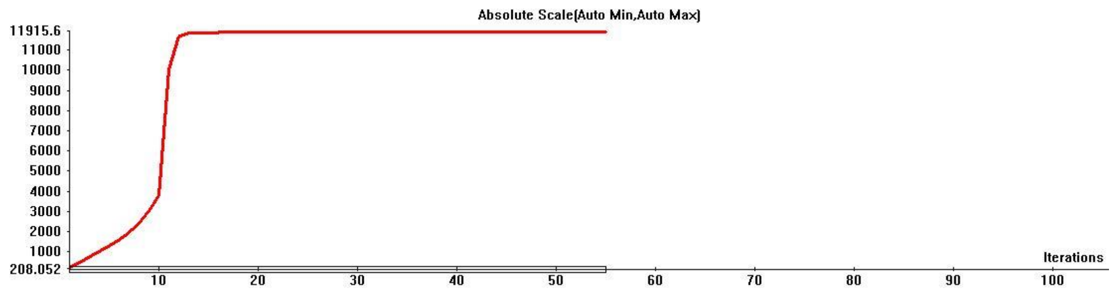
Output linear graph:



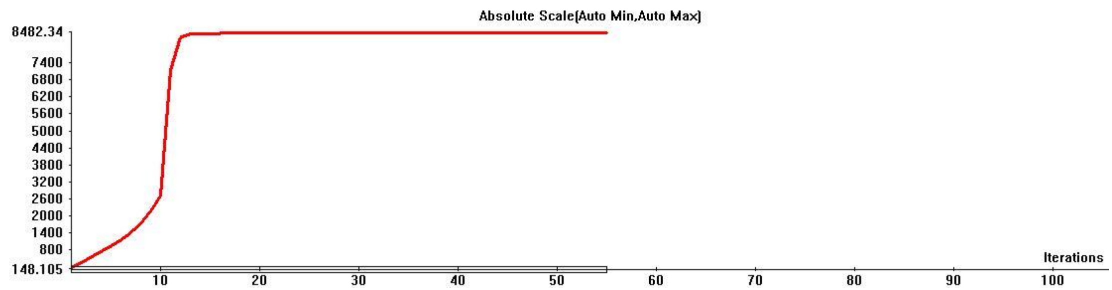
Temperature of the coil



Pipe temperature (average)



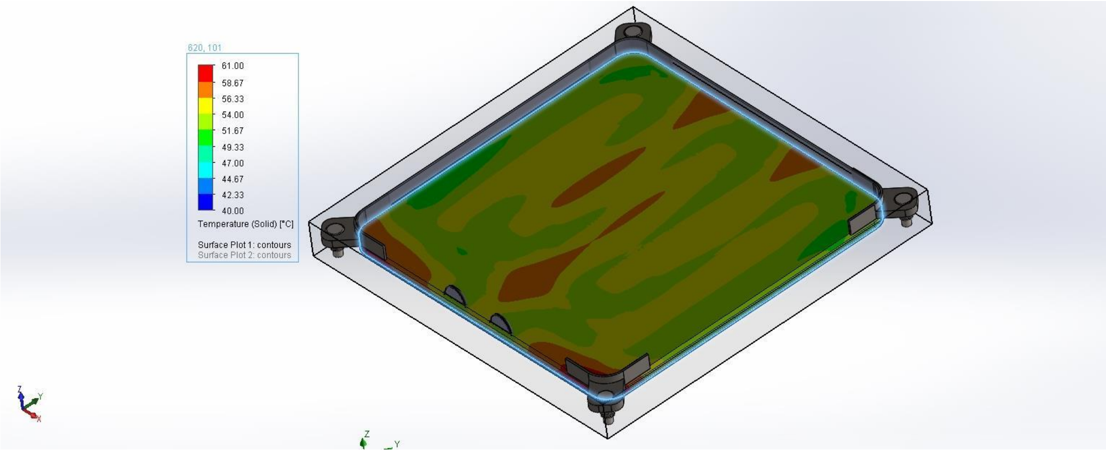
Surface heat flux of the coil (average)



Heat transfer rate of the coil (average)

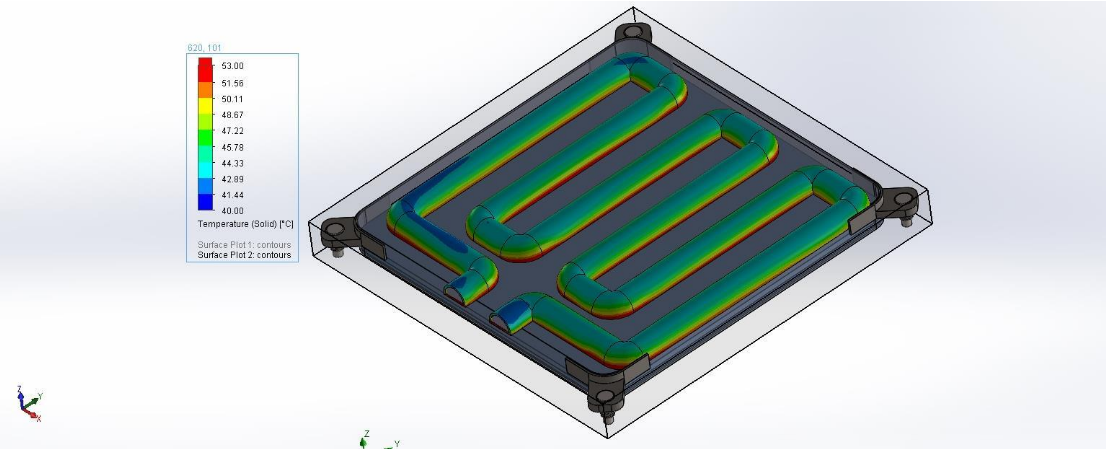
According to the results, the system is sensitive to the variation of the temperature. When the weather is hot, the increment of the temperature of the solids part is not a negligible amount. Significantly, the coil's average temperature adds 10℃ more, and the culmination of the temperature is over 60℃. As a consequence, the pipe's temperature is rising likewise, up to 49℃. Nevertheless, the heat transfer rate and the heat flux remain constant due to the input heat power not changed.

Results in simulated diagram:



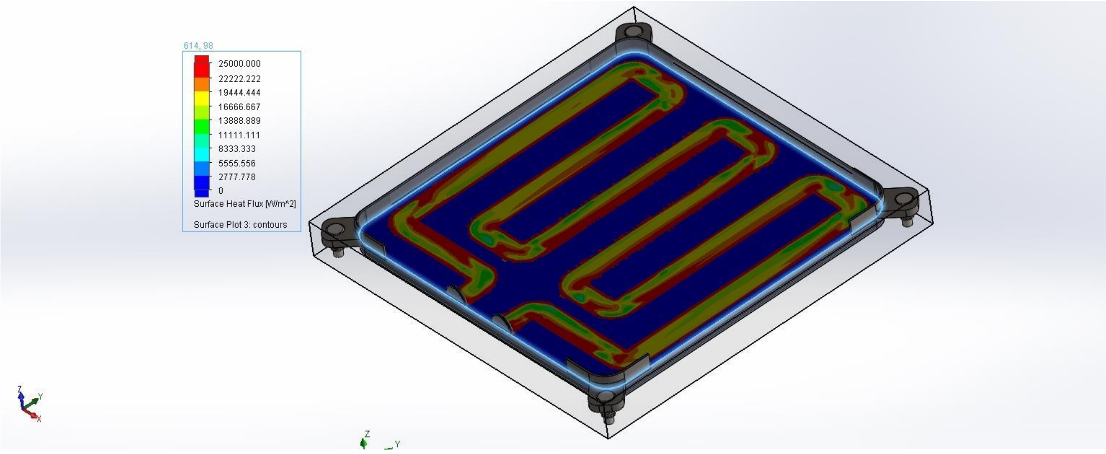
Temperature distribution of the coil

Absolutely, from the temperature table, the coil is thermal, and the high temperature region is inclined to expand. On the other hand, the distribution is similar with the case 2. Certainly, these regions are mainly non-contacted regions which refer the pipe does not cover them.



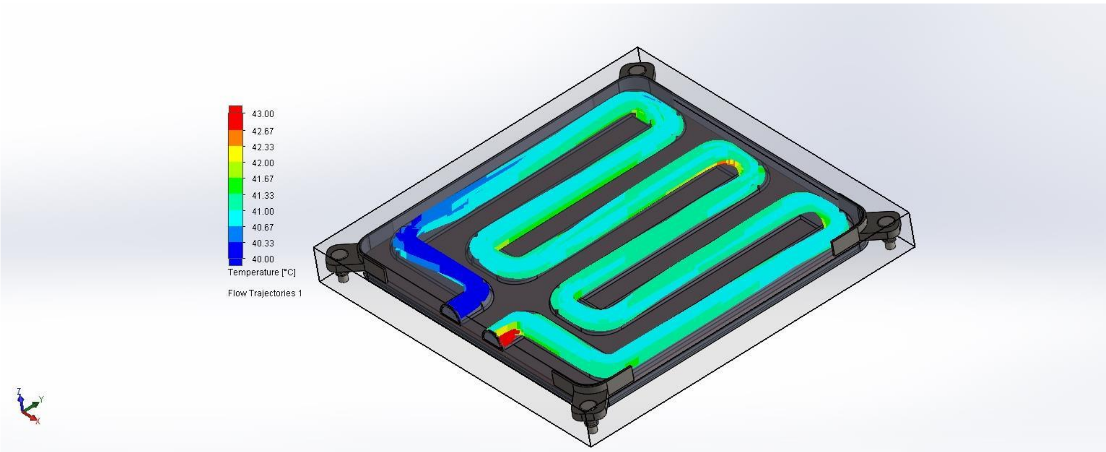
Temperature distribution of the pipe

The temperature distribution does not have too much variation; generally speaking the temperature ascends for both contact area and non-contact area.



The heat flux distribution

Depending on the photo, the heat flux almost retains at a constant level in distribution and the number. The reason is that the total amounts of the heat need to be released are equal, and even the temperature of water increasing, it still own the ability to absorb the heat power



Coolant temperature variation

Comparison with the coil, the increment of the temperature of the water is extremely tiny. After cooling down the coil, its temperature is no more than 43℃ as a result of the outstanding heat capacity of the water.

Case 4

In this case, assuming the solid is heated up to 65℃ (target temperature) and the coolant start to flow into the pipe. The cooling ability is tested, and hold the other setting is identical with the case 3. By the way, this kind of situation' likelihood in reality is close zero.

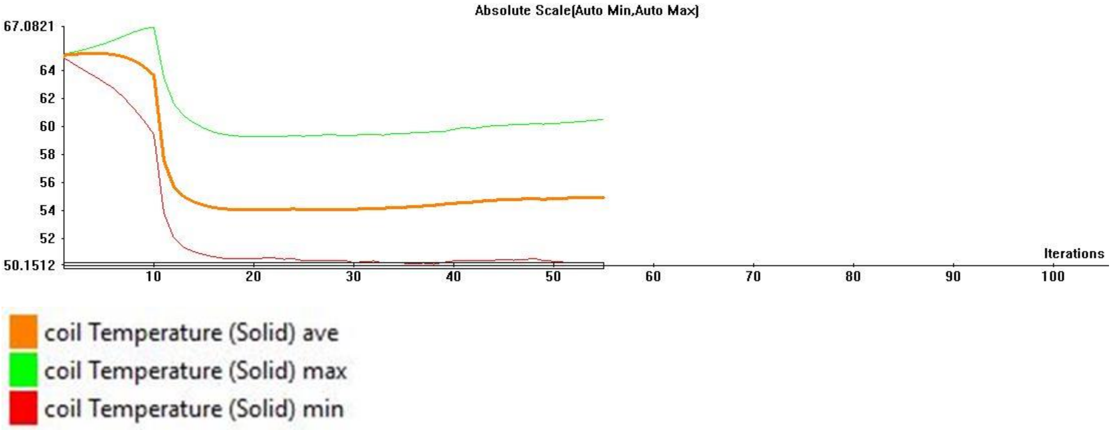
Input parameters:

Inital condition for solid:Temperature=65℃;

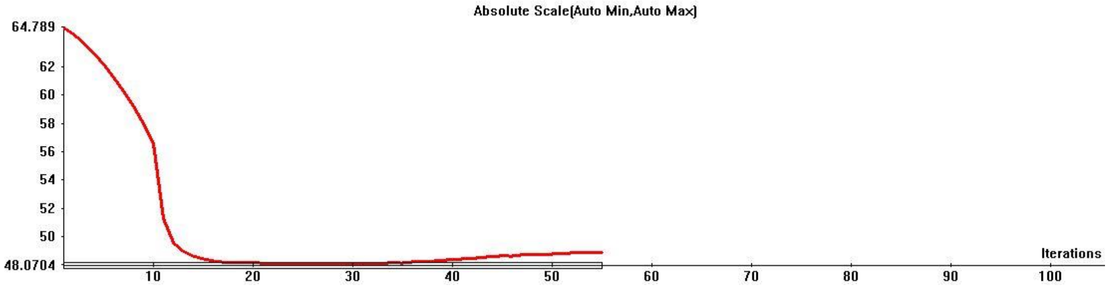
Inital condition for fluid:Temperature=40℃;

Outlet boundary condition: Presure=1atm; Temperature= 45℃;
Inlet flow rate=0.4kg/s;
Inlet flow speed: 1m/s (y-axis);
The power of heat: P=8500 W.

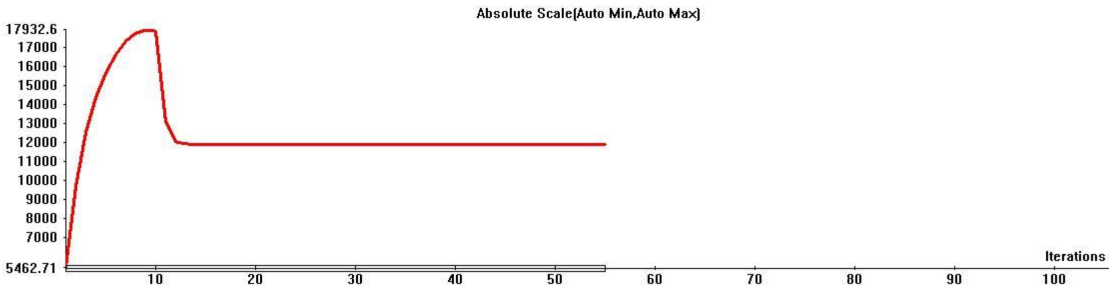
Output linear graph:



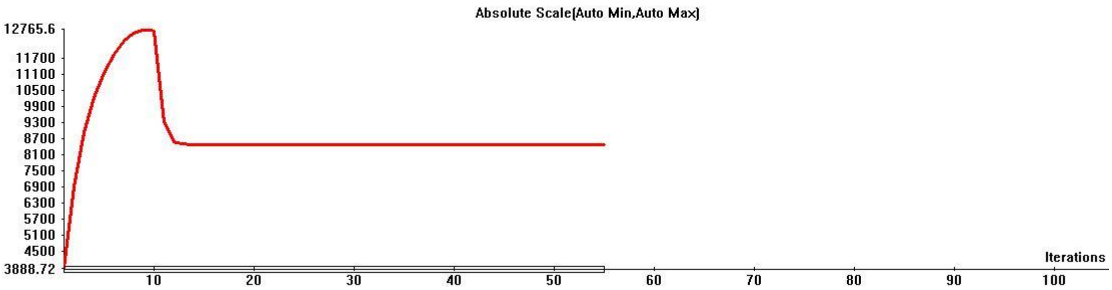
Temperature of the coil



Pipe temperature (average)



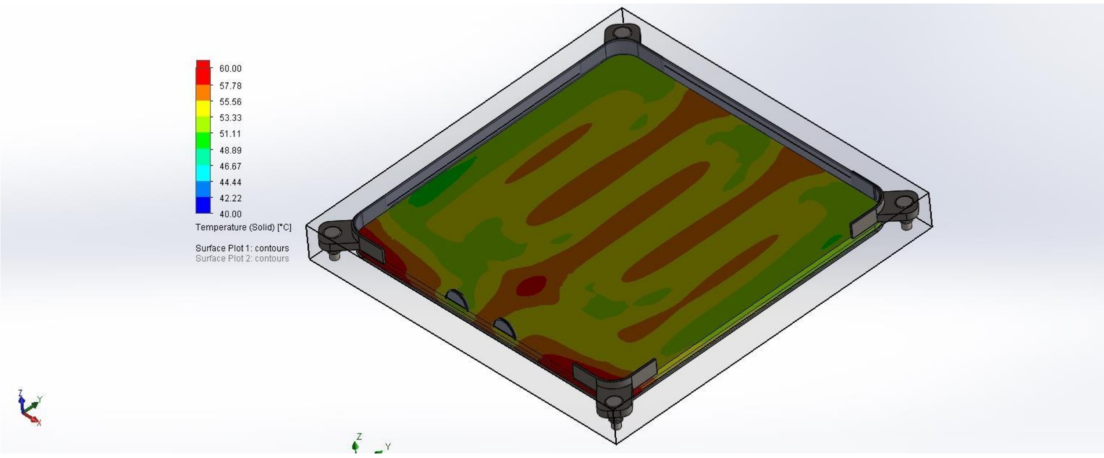
Surface heat flux of the coil (average)



Heat transfer rate of the coil (average)

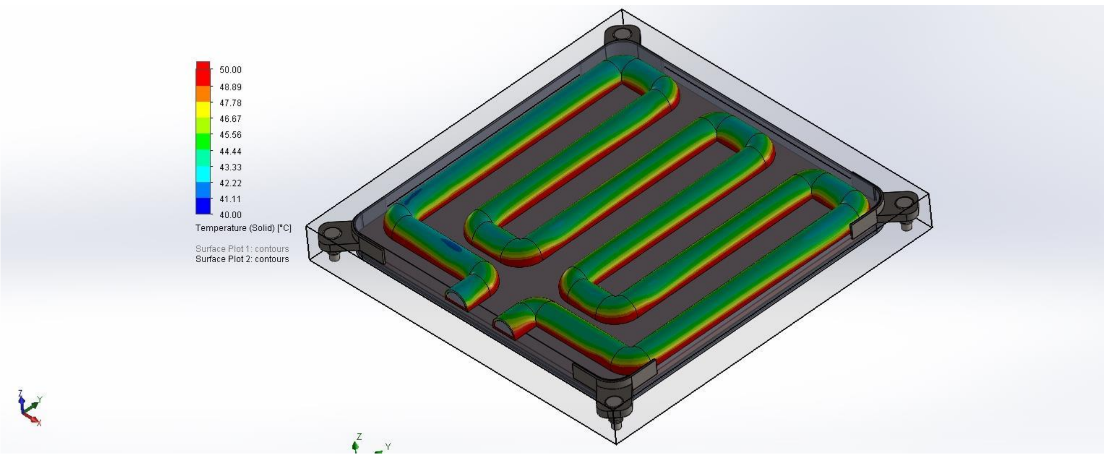
Overall, the inclination of these line graphs is obviously different with the previous cases. Frankly speaking, it depicts the cooling process. The temperature of the coil decreases as well as the pipe and later keeps at a stable state. Although the maximum temperature of the coil is up to 68℃, it is still tolerable and descends to a lower temperature. Besides, the heated coil releases more heat thanks to the high temperature. Both the surface heat flux of the coil and heat transfer rate initial at a gigantic value, and climbing to culminate at the same time, then it falls back and keep constant as before.
These data prove that even at sever and high temperature case, it system is capable to cool down the WPT and keep stable, when the coolant temperature is in a relative scaled state.

Results in simulated diagram:



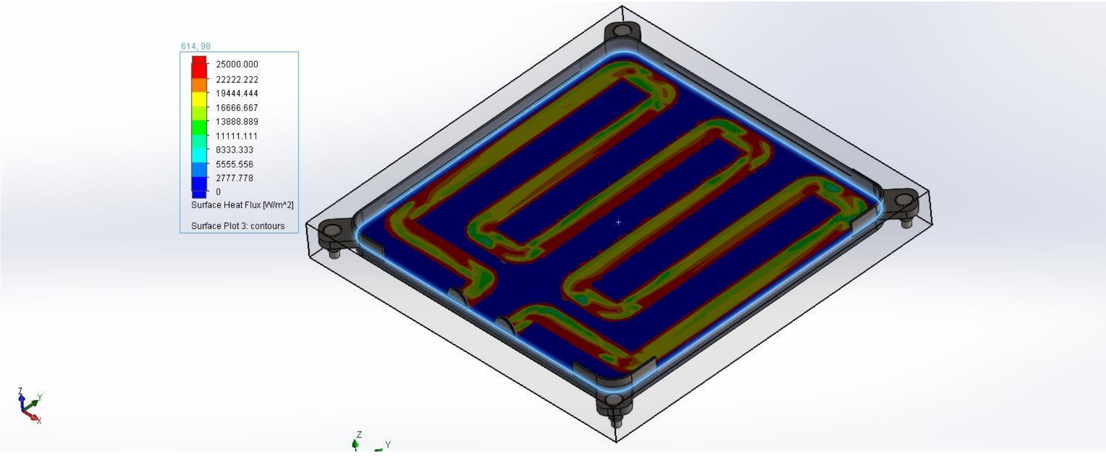
Temperature distribution of the coil

The high temperature region is extended and the value is higher. There areas appear in all the non-contact area.



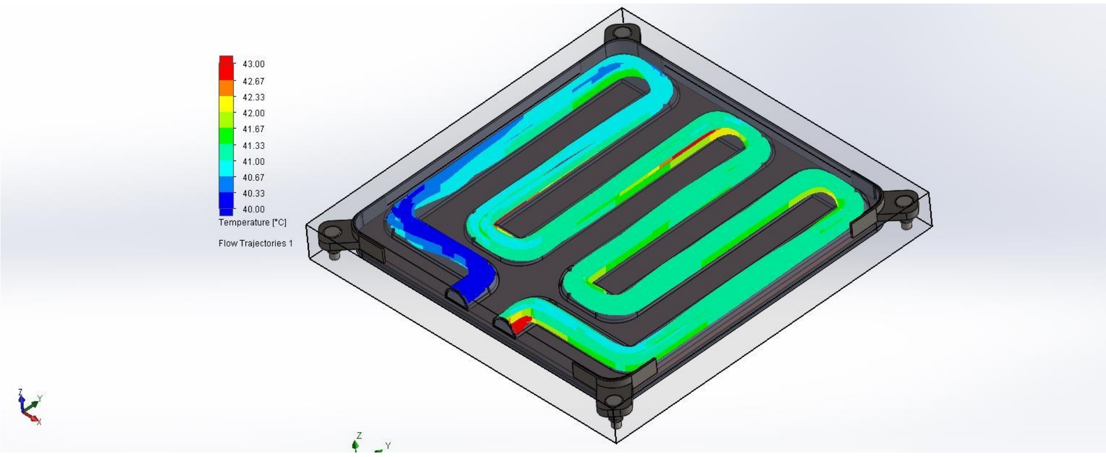
Temperature distribution of the pipe

The pipe is also hot at the beginning, but the temperature distribution is almost uniform expect a part of pipe close to the inlet port. Because the temperature different is large at the beginning, and the heat transfer and heat release rate is also high.



The heat flux distribution

The diagram of distribution of heat flux is no discrepancy comparing with the previous case. In the steady state, the heat flux is invariable and it just depends on the input heat power.



Coolant temperature variation

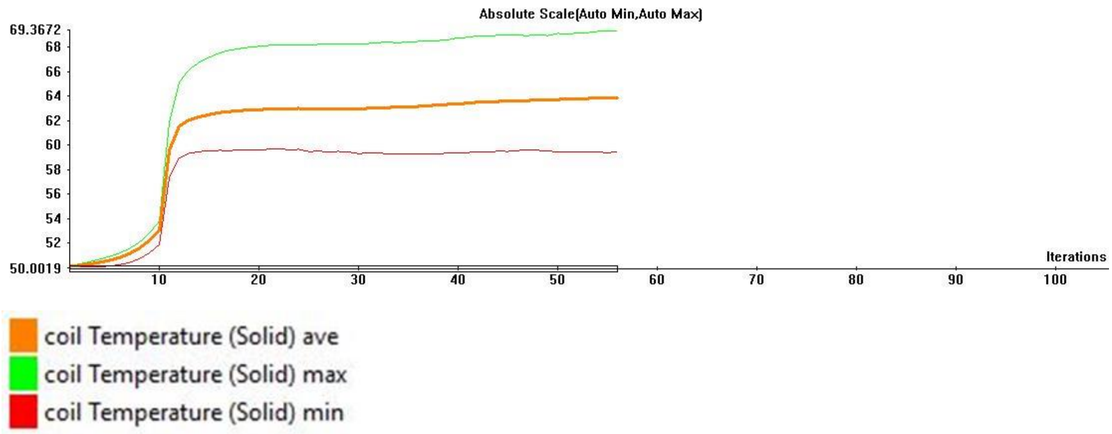
The temperature of the coolant is no doubly higher than Case 4, since more energy is demanded to be assimilated.

Case 5

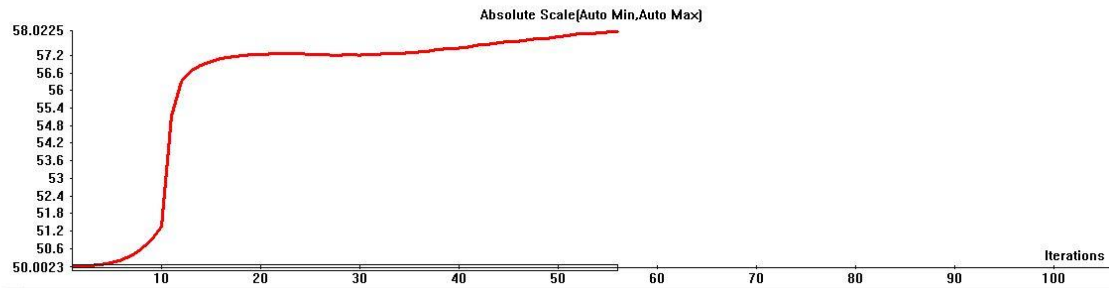
In order to approach the real condition, the initial temperature of the coil should not too much higher than the ambient temperature. The extremely condition for the real is in a hot weather, and the vehicle have operated for a long time, then battery energy required to be charged. Thus, the water temperature is higher for cooling other component and without dissipating the heat by condenser. The temperature of the solid and fluid begin at 50°C.

Input parameters:
Inital condition for solid:Temperature=50℃;
Inital condition for fluid:Temperature=50℃;
Outlet boundary condition: Presure=1atm; Temperature= 55℃;
Inlet flow rate=0.4kg/s;
Inlet flow speed: 1m/s (y-axis);
The power of heat: P=8500W.

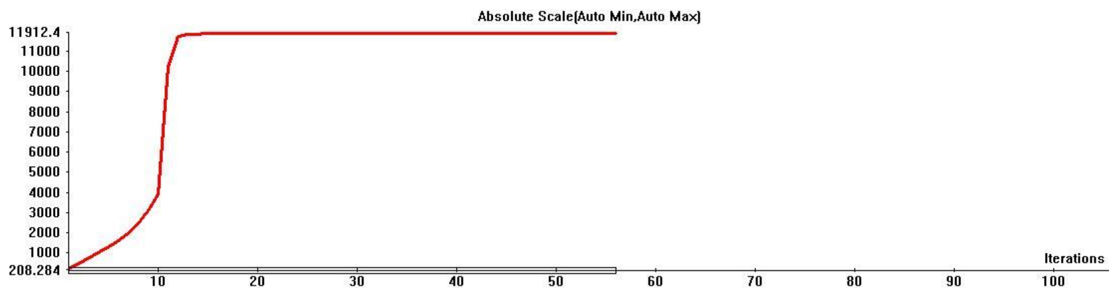
Output linear graph:



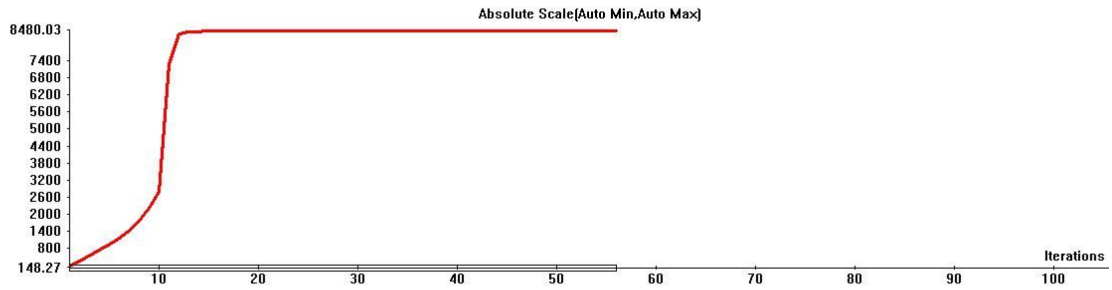
Temperature of the coil



Pipe temperature (average)



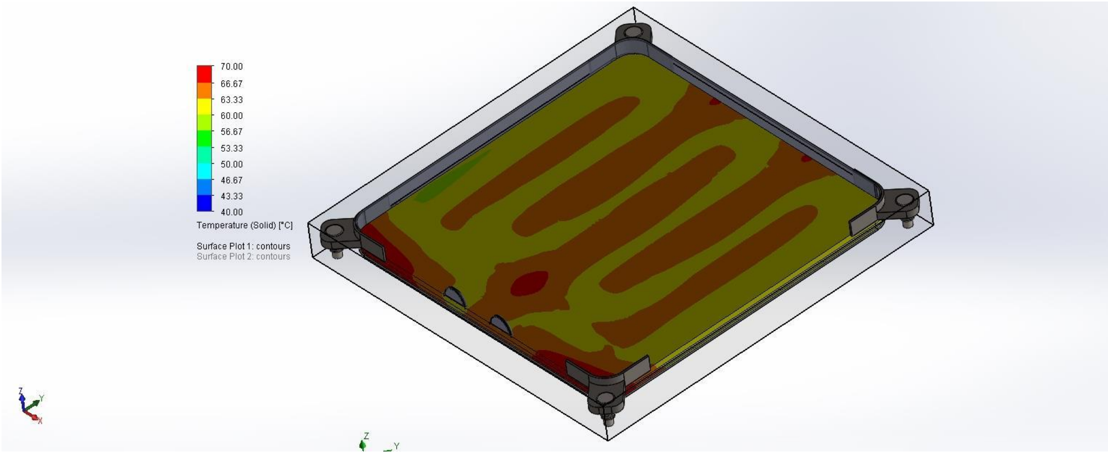
Surface heat flux of the coil (average)



Heat transfer rate of the coil (average)

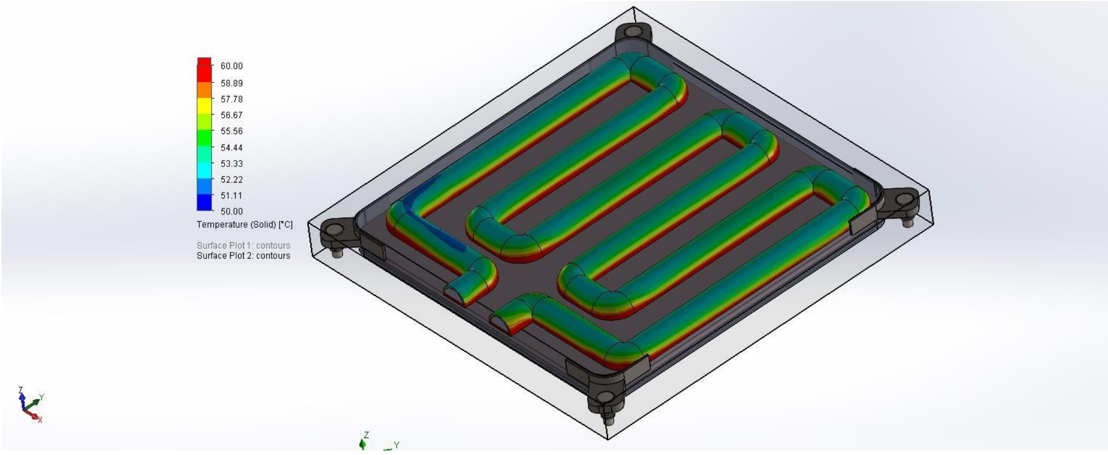
Because fixed the input power at 8500W, the heat transfer and heat flux remain the same. However, the temperature of the solid and fluid increase under the effect of the heat power. Moreover, the coil temperature is higher than previous case, the maximum of the temperature is near close to 70℃, and the average temperature is steely rising to around 62℃. The temperature is near the limit.

Results in simulated diagram:



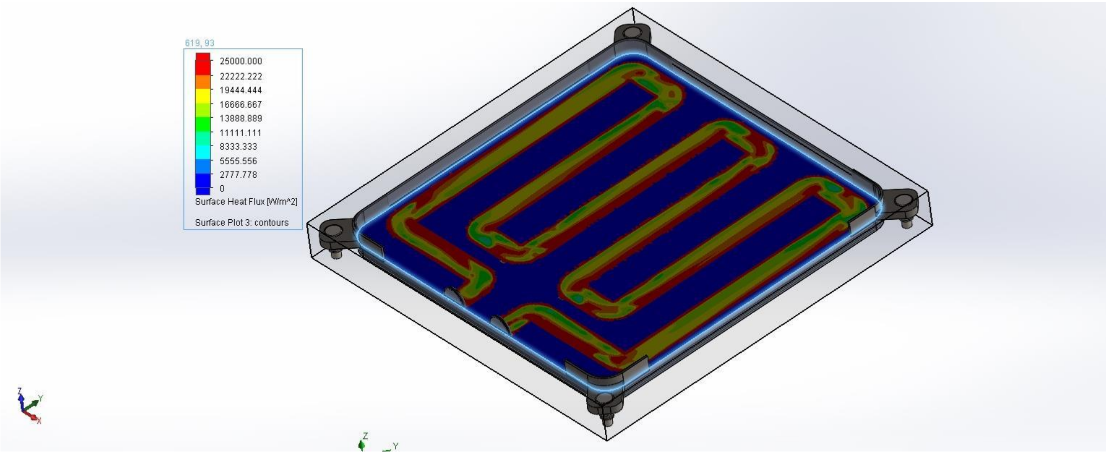
Temperature distribution of the coil

From that scheme, the high regions further extend, which approximately half the total area and the green part (low temperature region) is almost vanished.



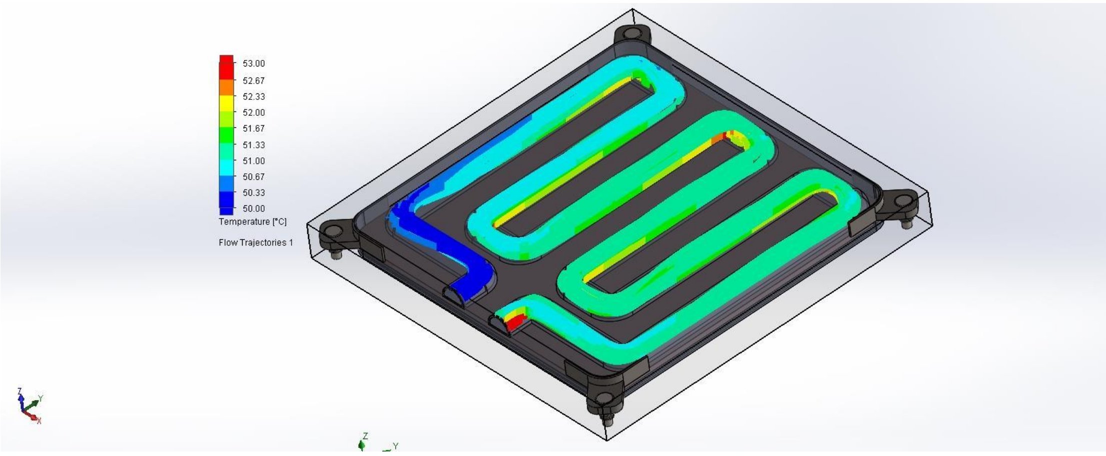
Temperature distribution of the pipe

The pipe is also heated by the coil, the heat transfer from the contact surface of them and the temperature reduced with respect to the height of the pipe. The temperature ascends about 8℃.



The heat flux distribution

Still, no matter how the temperature of the ambient changed, the heat flux always remains at the constant.



Coolant temperature variation

The coolant temperature rising to around 52.5℃ in the circuit, and the temperature is climbing slowly from inlet to the outlet.

3.3 Summary

From the different cases, seemingly, the high temperature regions of the coil are located in the uncovered area, and the area of the high temperature regions is strongly influenced by the temperature of the solid and coolant. With the temperature increasing, the high temperature region is inclined to expand their border.

From the performance perspective, it can be concluded that the coolant temperature is better controlled around 40℃ to keep the temperature of the coil in the target range. In addition, when the coolant and the solid are heated at the same temperature, regardless the value of the initial temperature and coolant, the increment number in temperature may be a certain value. For the coil, the increment is about 20℃, and 8℃ for the pipe. For the fluid, the value is in the interval 2℃ to 3℃, because the heat capacity of the water is not a constant in different pressure and temperature.
Furthermore, the material for the coil and pipe are simplified from the thermal point of view. In real situation, the coil should be covered by insulated materials to prevent the current transfer to the coolant, because all the material here is mainly metal. The metal is conductive. Thus, these kinds of material will interact with the heat transfer process. Unfortunately, the information about the charging system is insufficient, so this factor is neglected.
On the other hand, the simulations still miss an important factor. The inlet temperature will not be a constant regardless integrated with the cooling system with the vehicle or a special one for it. The reason the tank of coolant is not infinite in reality, and the tank has a certain volume and the temperature is varied following the cooling progress.
Last but not least, it's not accuracy to apply the water as the coolant in the simulation. In automotive flied, some additive is mandatory such as glycol, which is acting as anti-freezing in the cold weather. And the properties of the coolant will also change. The results obtained here just as a reference for the further research.

Chapter 4

Modules of the structure

In order to consider a more real condition and find out that whether the WPT could share the same cooling system with the existing one, and temperature of battery and WPT is acceptable or not. The layout of the cooling system will be built for simulation, and the software for this purpose is Simulation-X. Besides, in this software, the charging time can be taken into account, and the coolant is also sufficient in selecting the mixture 50% water and 50% glycol. The utilized blocks are thermic and thermic fluid.

4.1 Open loop simulation

To see the influence of the WPT system to the vehicle cooling system, a circuit of coolant is established to simulate the temperature variation during the charging progress in 5 minutes. Besides, the tank is regard as a boundary condition, thereby, the temperature will keep constant. Plus, depending on the result from the Solidworks, starting from the heated battery and coil in 50℃ and 65℃ respectively. Relevant parameters are following:

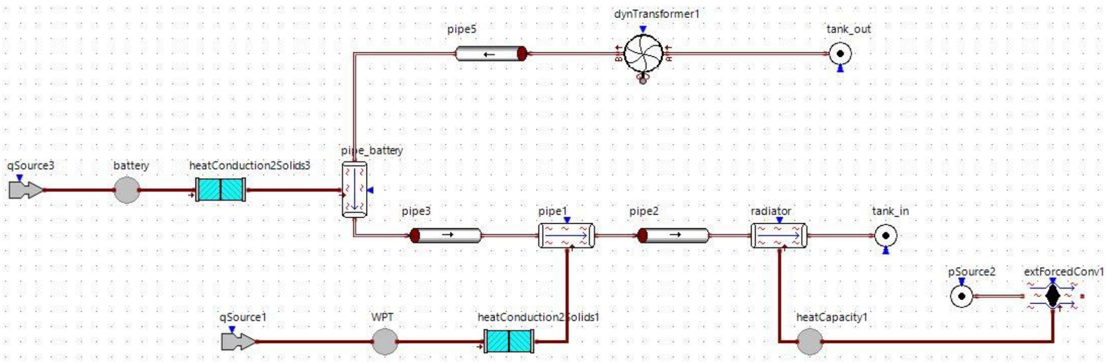
Input data:
General setting:
Simulation time=300s;
Ambient temperature=25℃;
Initial pressure=1atm;
Coolant flow rate=0.4 kg/s.
Coolant initial temperature=40℃;
Coolant type: 50% water 50% glycol

Battery setting:
Heat release from battery=5KW;
The battery weight=260kg;
The heat capacity of the battery=1.1KJ/(kg·∗ ℃);
Battery initial temperature=50℃;
Cooling pipe length=15m;
Cooling pipe width=10mm
Cooling pipe height=10mm;
Contact area between pipe and battery=150000mm^2.

WPT setting:
Heat release from coil system=5KW;
The coil weight=50kg;
The heat capacity of the coil=1.6 KJ/(kg·∗ ℃);

Coil initial temperature=65°C;
Cooling pipe length=5m;
Cooling pipe radius=30mm
Contact area between pipe and coil=318900mm^2.

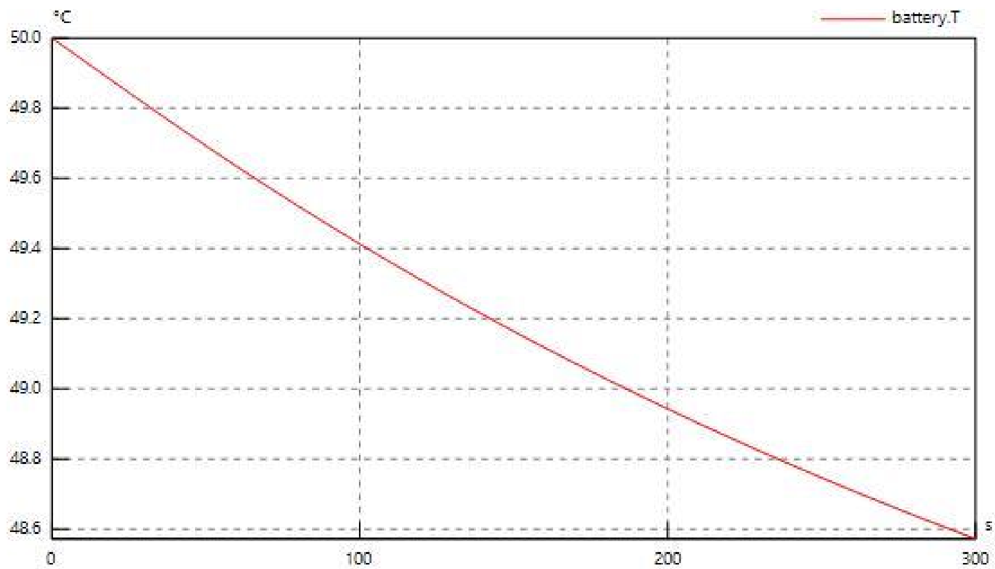
Radiator setting:
Cooling pipe length=508mm;
Cooling pipe radius=18mm;
Number of pipes=6;
Air flow rate=1kg/s.



Open loop layout

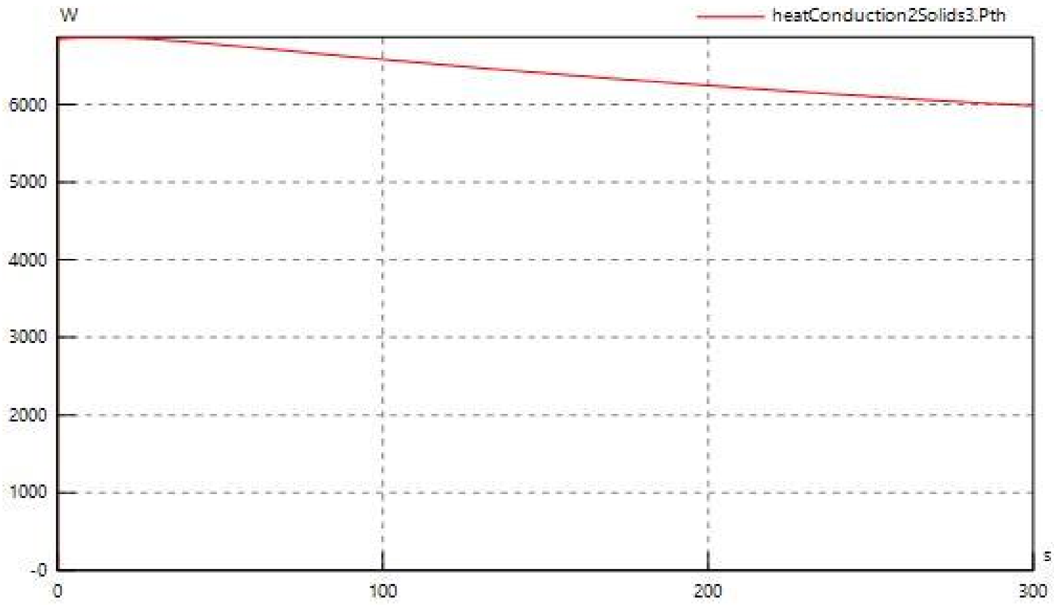
The coolant storage is in the tank at beginning. When the charging is active, the pump absorbs the coolant from the tank, then through the pipe to the cooling channel of the battery. After cooling the battery, the flow runs into the WPT system to assimilate the heat. Later, the heat insides the coolant releases to the environment via the radiator. Eventually, the coolant returns to the tank.

Results:



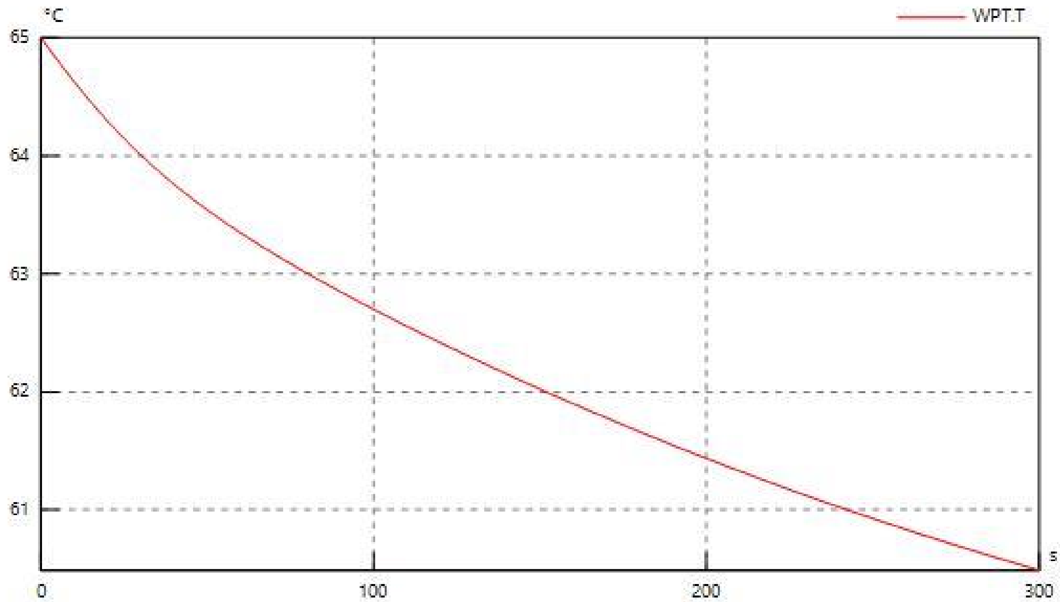
Temperature of the battery

The outcome is a linear diagram. It reports in the 5mintes, the temperature of the battery decreased, but the decrease is tiny. The temperature only reduces 1.4℃, from 50℃ to 48.6℃.



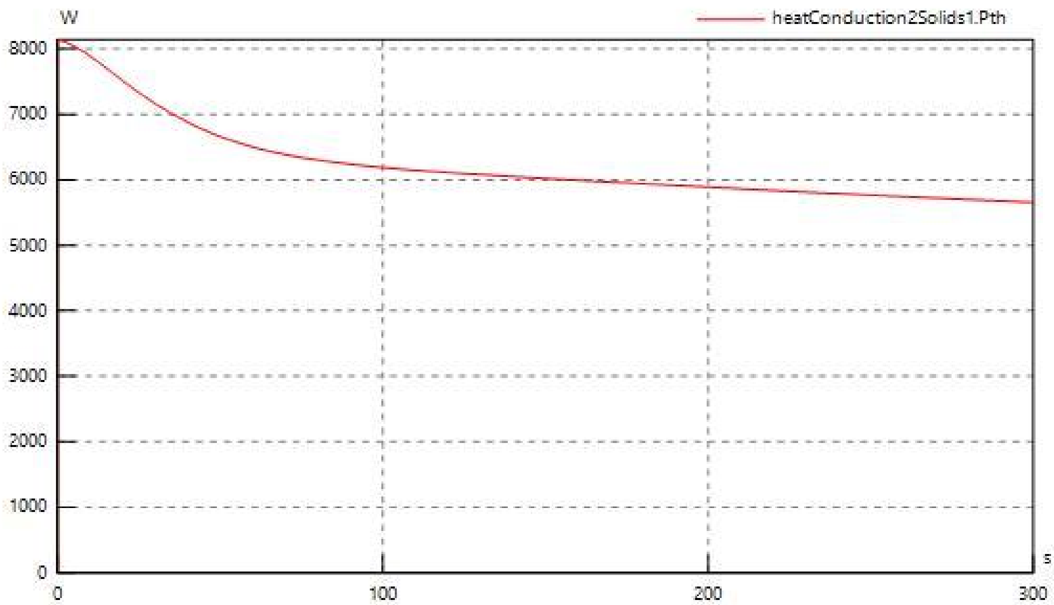
Heat transfer rate of battery

The diagram is illustrates the heat transfer between the coolant and the battery, which is obtained from the cooling pipe of the battery. At the beginning, the transfer rate is high, but with time goes by, the rate tend to go down.



Temperature of WPT

Seemingly, the temperature of the WPT under controlled as well. It falls from the 65℃ to the nearly 60.5℃.



Heat transfer rate of WPT

From the heat transfer rate between the coolant and the WPT, it's faster than the battery. As consequence, the temperature of the WPT goes down more quickly.

4.2 Close loop simulation

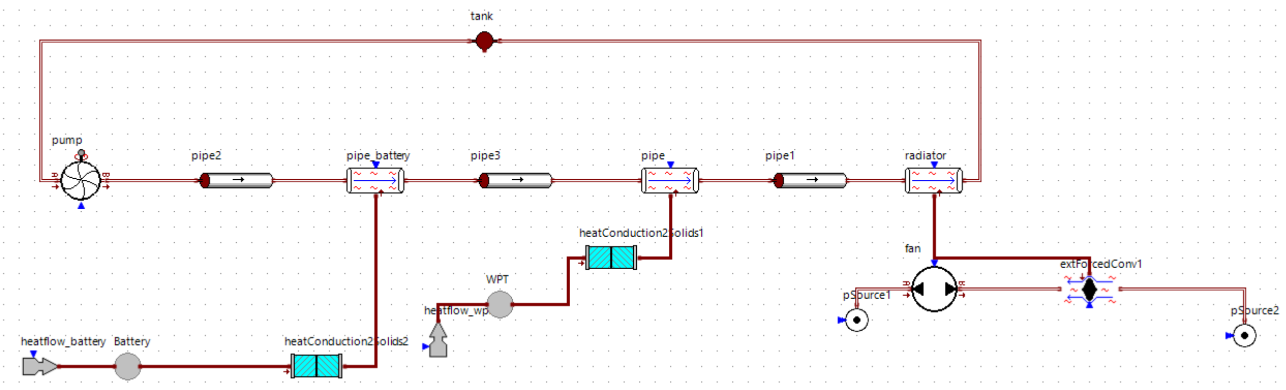
Contemplate the issue in simulation of Solidworks: the coolant temperature is not a constant. The inlet temperature of the cooling channel of battery and WPT system will be affected. In the open loop, the variation of the inlet temperature of coolant for WPT system is solved, where the coolant is heated before flowing into the WPT system. Whereas, the flow in the inlet port of the battery is still constant. Thus, the temperature of the reservoir should take into account.

Input data:
General setting:
Simulation time=300s;
Ambient temperature=25℃;
Initial pressure=1atm;
Coolant flow rate=0.4 kg/s.
Coolant initial temperature=40℃;
Tank volume=50L;
Coolant type: 50% water 50% glycol.

Battery setting:
Heat release from battery=5KW;
The battery weight=260kg;
The heat capacity of the battery=1.1KJ/(kg·∗ ℃);
Battery initial temperature=50℃;
Cooling pipe length=15m;
Cooling pipe width=10mm
Cooling pipe height=10mm;
Contact area between pipe and battery=150000mm^2.

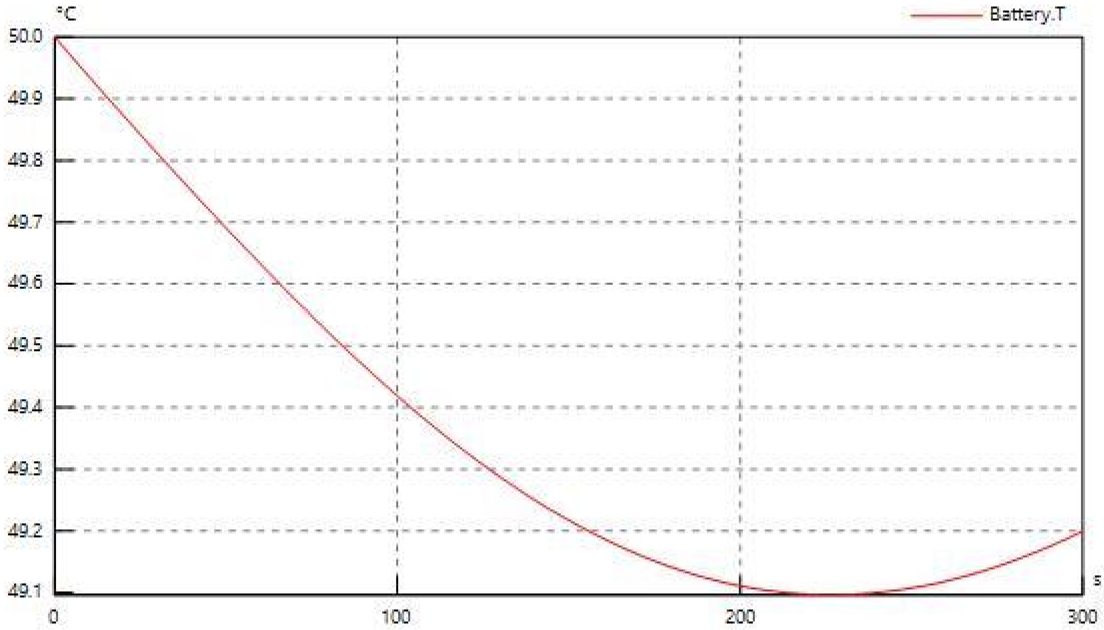
WPT setting:
Heat release from coil system=5KW;
The coil weight=50kg;
The heat capacity of the coil=1.6 KJ/(kg·∗ ℃);
Coil initial temperature=65℃;
Cooling pipe length=5m;
Cooling pipe radius=30mm
Contact area between pipe and coil=318900mm^2.

Radiator setting:
Cooling pipe length=508mm;
Cooling pipe radius=18mm;
Number of pipes=6;
Air flow rate=1kg/s.



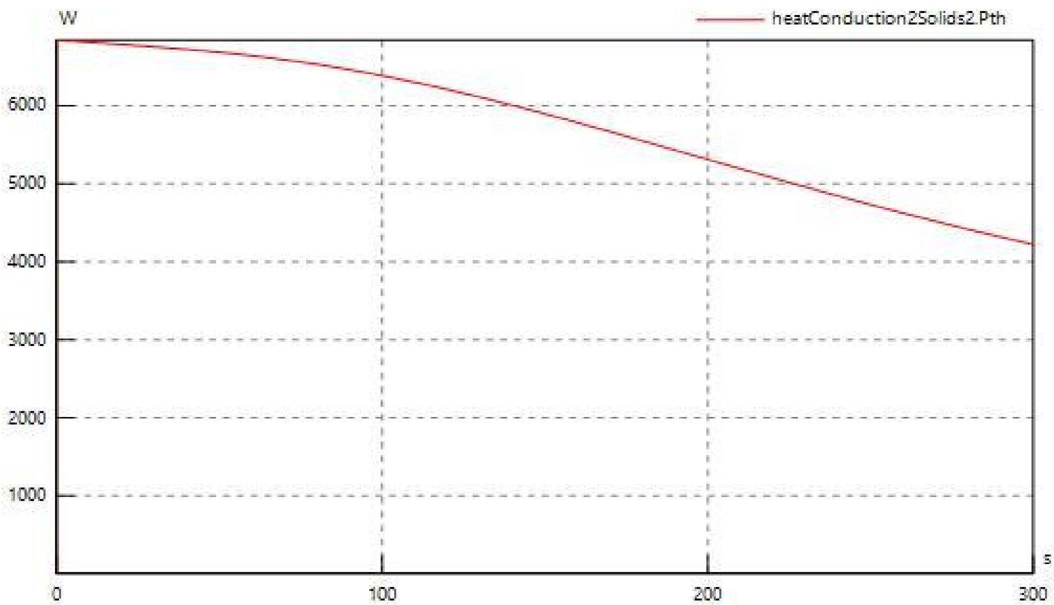
Layout of the cooling system

Without changing the parameters, the layout becomes the close loop. The tank is not a boundary condition any more. And the reservoir owns the volume which is 50L; the value is estimated by the volume of the cooling pipe for battery and WPT system. It is essential to fill the volume of these cooling pipes.
Hence, the volume source substitutes the pressure source. Thanks to that, the circuit is able to fulfill the close loop, which is more approach to the real conditions.



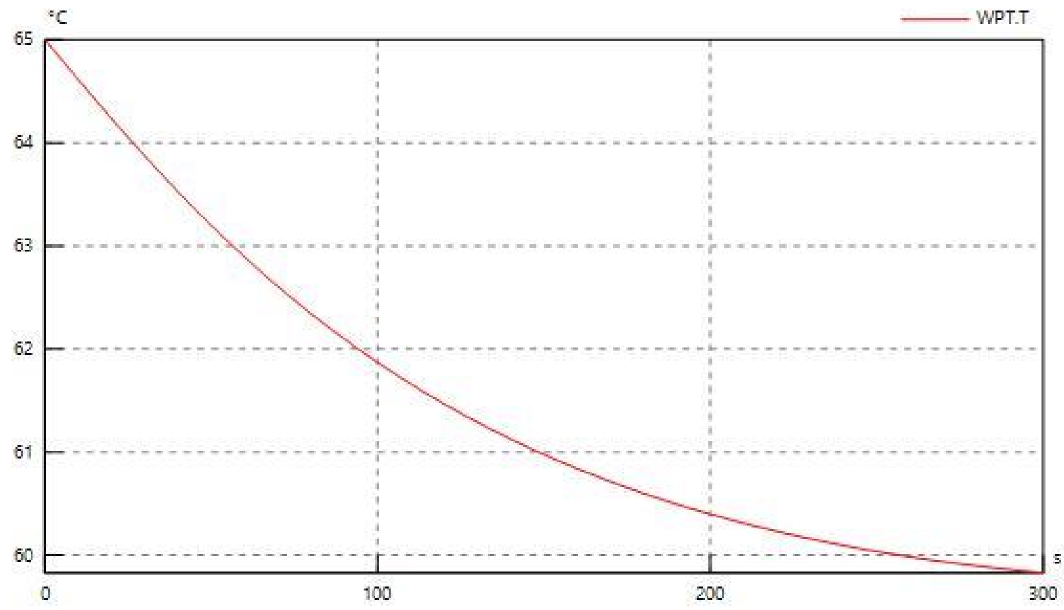
Temperature of the battery

The battery's temperature is also restrained, but the temperature is even close to 50℃. After 200s, the temperature reaches the minimum value approximately 49℃. Later, it tends to increase.



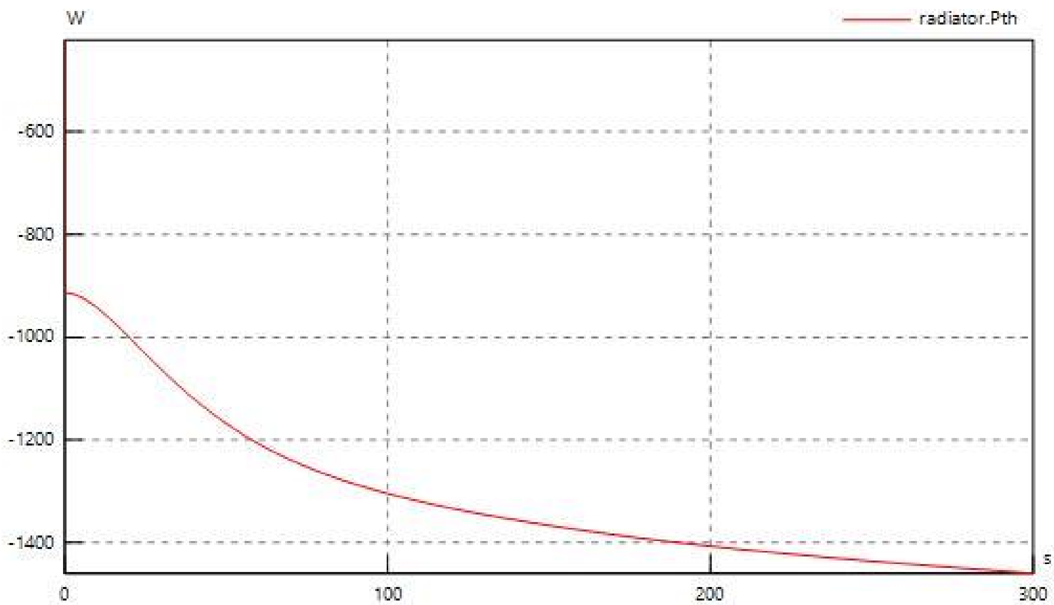
Heat transfer of the battery

The graph of heat transfer explains the reason. The rate of heat transfer is continuously slow down. At the minimum temperature point, the rate is exactly 5000W, which compensates the input heat power. Later, the rate still reduces, as a result of that, the temperature start to rebound.



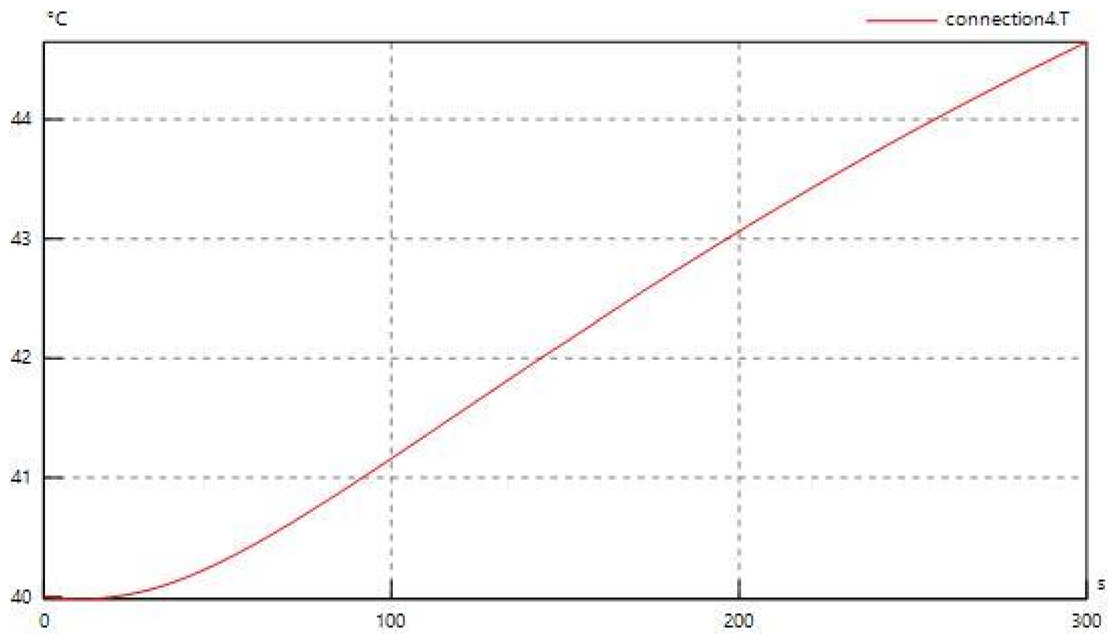
Temperature of WPT

Meanwhile, the temperature of the WPT system is tolerable. In 300s, it does not happen the rebounding.



Heat transfer rate of the radiator

The heat released to the ambient through the radiator. Due to the temperature's discrepancy increasing, the power dissipated also rises. The value is negative standing for the transfer direction, which is opposite with that for coil and battery.



Temperature of coolant tank

From the volume source called tank, it is easy to monitor the temperature changing in the 5 minutes. The temperature is continuously climbing because the input heat power from battery and coil is larger than the dissipated by the radiator.

Basis on the Case 5 in the simulation of Solidworks, the parameters is required to be defined to close to the real extremely case. Since, still simulate in the close loop layout. Resemble the Case 5, the environment temperature is 40℃ and the coolant and solid part are 50℃.

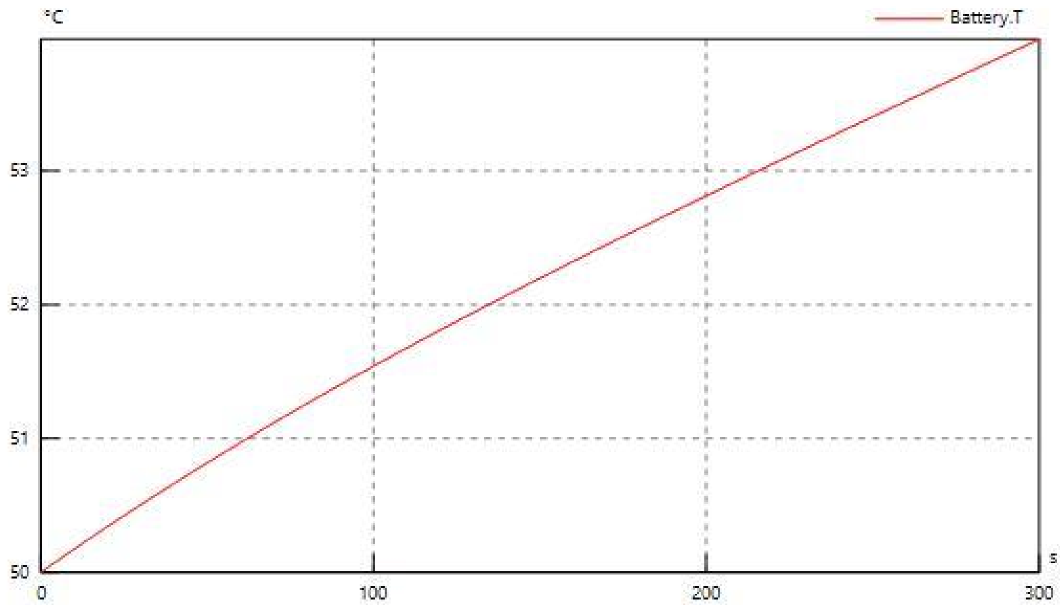
Input data:
General setting:
Simulation time=300s;
Ambient temperature=40℃;
Initial pressure=1atm;
Coolant flow rate=0.4 kg/s.
Coolant initial temperature=50℃;
Tank volume=50L;
Coolant type: 50% water 50% glycol.

Battery setting:
Heat release from battery=5KW;
The battery weight=260kg;
The heat capacity of the battery=1.1KJ/(kg·∗ ℃);
Battery initial temperature=50℃;
Cooling pipe length=15m;

Cooling pipe width=10mm
Cooling pipe height=10mm;
Contact area between pipe and battery=150000mm^2.

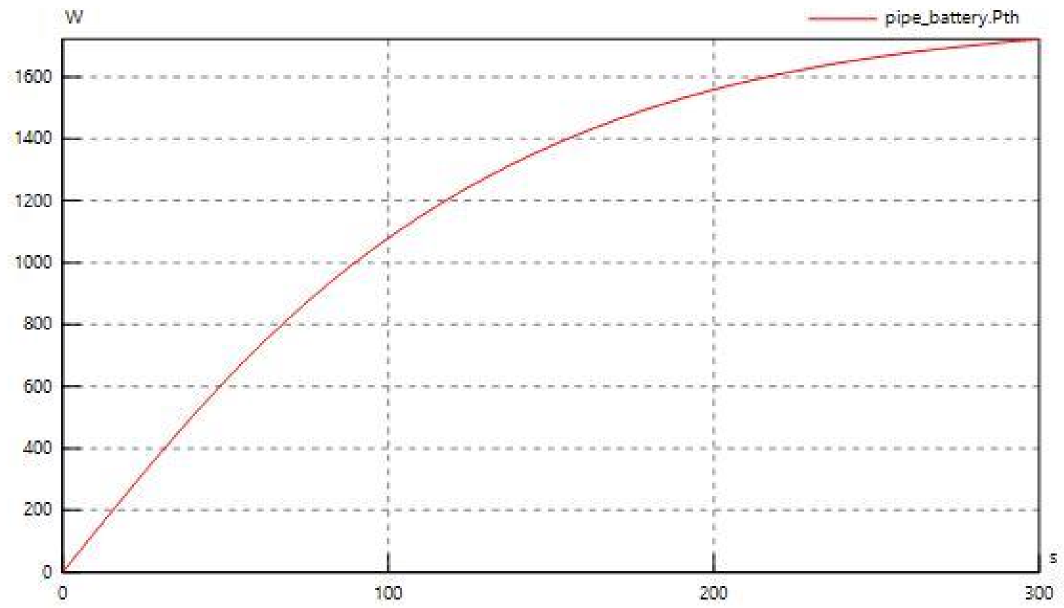
WPT setting:
Heat release from coil system=5KW;
The coil weight=50kg;
The heat capacity of the coil=1.6 KJ/ (kg·$*$ ℃);
Coil initial temperature=50℃;
Cooling pipe length=5m;
Cooling pipe radius=30mm
Contact area between pipe and coil=318900mm^2.

Radiator setting:
Cooling pipe length=508mm;
Cooling pipe radius=18mm;
Number of pipes=6;
Air flow rate=1kg/s.



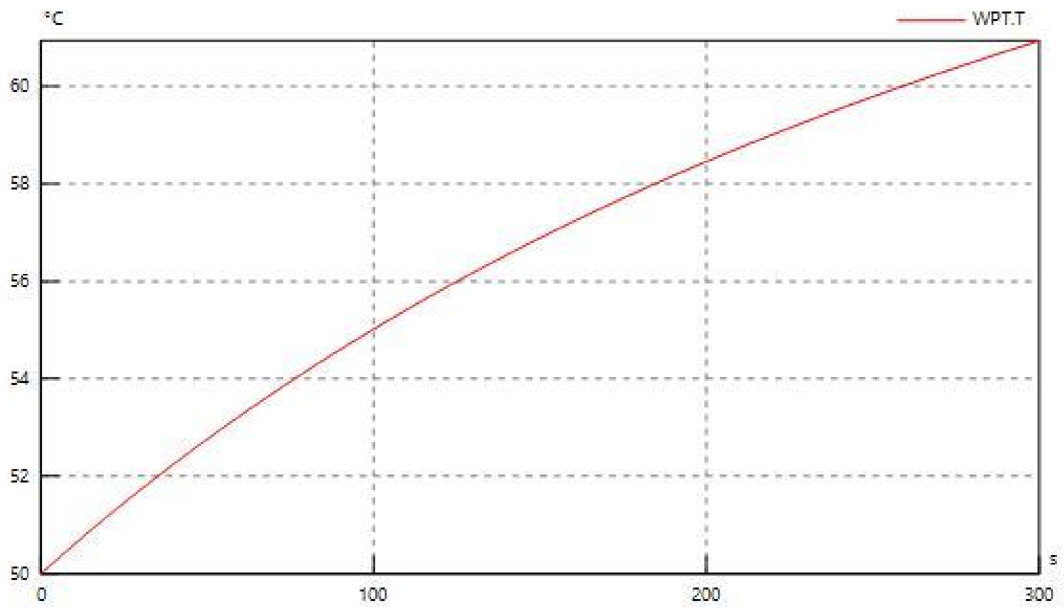
Temperature of the battery

Reference to the results in Case 5, the temperature will rise when the coolant and the solid part share the same temperature. In this situation, the battery's temperature mounts up to 54℃.



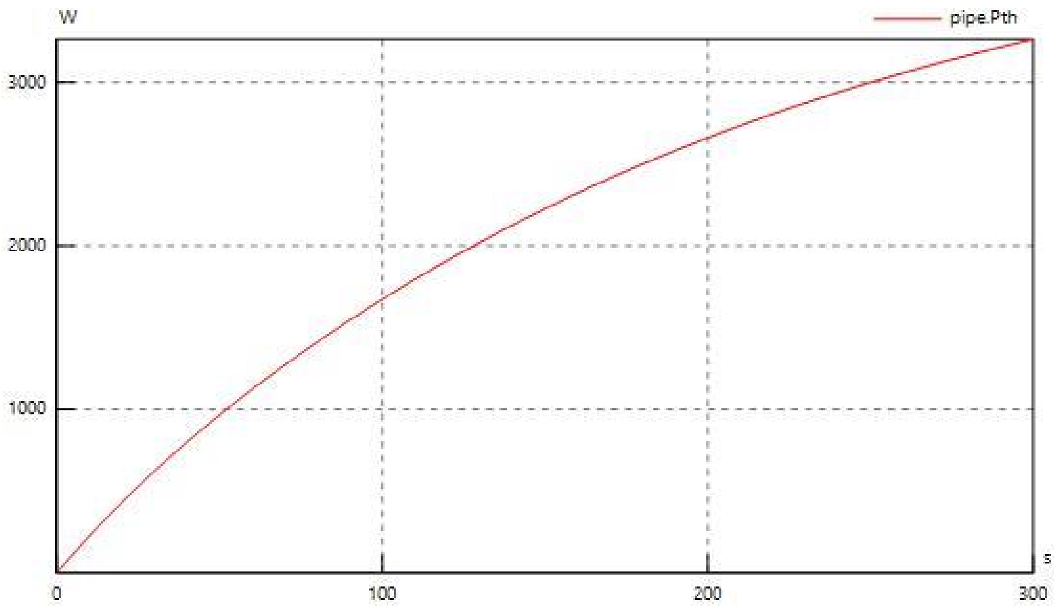
Heat transfer of the battery

Correspondingly, the heat transfer rate is very low, because the temperature difference is not significant. But, it keeps rising caused by the difference of temperature in coolant and battery is increasing.



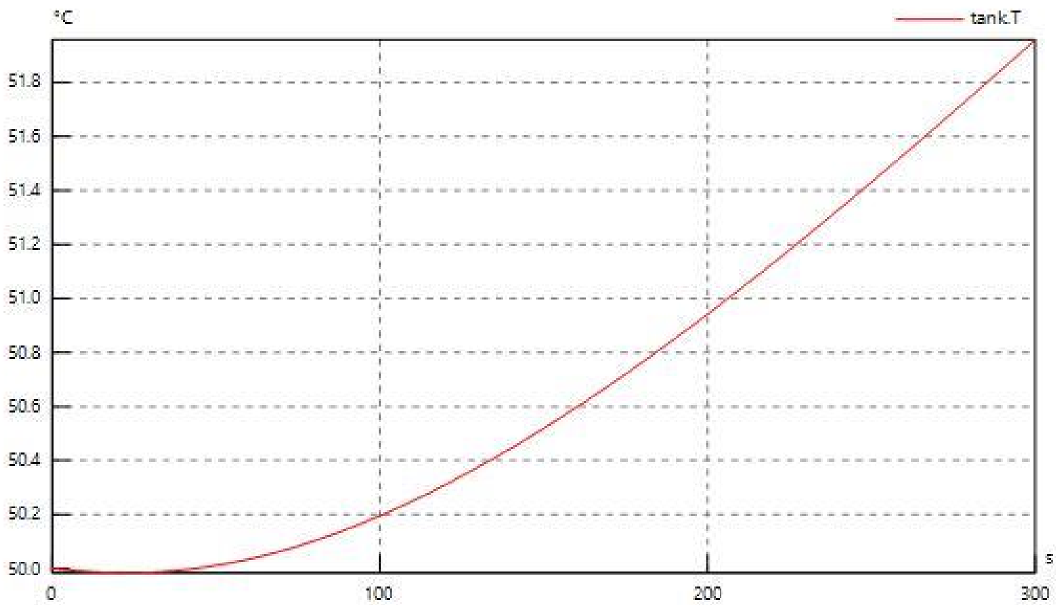
The WPT temperature

The temperature of WPT system increases in faster speed. In 300s, it mounts up over 60°C. The mass of the coil leads to the phenomenon. The coil's mass is lower than the battery, as a result of that, given the same amount of heat input, the temperature of the coil shall have a more increment to absorb the heat.



Heat transfer of the WPT

Because the temperature of the WPT system is relative higher, the heat transfer rate is fast. The speed is double than that for battery.



Coolant temperature

It's more clearly when the coolant temperature reported. The coolant temperature increases in a low speed, which leads to the temperature difference. The discrepancy between the coolant and battery is much less than that between coolant and coil.

Chapter 5 Conclusion

Combining the two software results, it leads to several conclusions to the thermal management about the Electric Vehicle.

5.1 Current situation

The results from Solidworks and SimulationX do not match each other perfectly. There are some discrepancies between them. However, the results obtained from SimulationX are more extremely, so it has the worthy in reference.
Basis of the results, although several factors like insulated material does not involved inside the calculation, it’s obvious that the integrated cooling system has the capability to accept the WPT system even in the severe case, and it’s no necessary to build a additional cooling circuit for the wireless charging system, and the complexity of the vehicle will not be improved.
Consider the performance of the charging system, the temperature of the coil is supposed to be a lower level. Therefore, the target temperature range for coil and battery is reasonable. It is suitable for the security and performance and the structure of the WPT cooling system is not very complicated likewise.
Particularly, the coolant temperature is better under 40℃. It not a very low temperature, thus, it is not a difficult task to keep the temperature by the current technology. For instance, the condenser is the ideal equipment.
Still, the actual cost should be considered, high cost on the structure is negative in profit. Actually, the maximum acceptable temperature of the coil is 100℃. The simulated results are far from the number and the designed model is absolutely suitable.

5.2 Solution

Adding the condenser is no doubly raising the system cost. Thus, from the economic point, the designed model is supposed to be even more simplified in order to save the cost.
There is a possible method for the purpose, which reduce the pipe contacting area, the length, radius, or height. In this way, the cost on material and manufacturing is less. Certainly, the temperature of battery and coil will close to the limit.

Bibliography

[1] E. Campagnoli, “Lecture notes (10th week)”, 05, 2015.
[2] Stefano d’Ambrosio, “Engine cooling system”, 2018.
[3] Seungyoung Ahh, “On-line Electric vehicle project and Vehicular Wireless Power Transfer Technology”, 04, 2017.
[4] Roman Bosshard；John W.Kolar, “Fundamental and Muti-object Desgin of Inductive Power Transfer system”, 2015.
[5] Sandeep Dhameja, “Electric vehicle battery system”, 2002.
[6] Ruffo Riccardo; Cirimele Vincenzo; Diana Michela; Khalilian Mojtaba; La Ganga Alessandro; Guglielmi Paolo (2018), “Sensorless control of the charging process of a dynamic inductive power transfer system with interleaved nine-phase boost converter”, In: IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,2018.
[7] F. Deflorio ; P. Guglielmi; I. Pinna; L. Castello; S. Marfull (2015) Modeling and Analysis of Wireless “Charge While Driving” Operations for Fully Electric Vehicles”, In: TRANSPORTATION RESEARCH PROCEDIA, 2015.
[8] Rosu Stefan George; Khalilian Mojtaba; Cirimele Vincenzo; Guglielmi Paolo (2016), “A Dynamic Wireless Charging System for Electric Vehicles Based on DC/AC Converters with SiC MOSFET-IGBT Switches and Resonant Gate-Drive”, In: IECON2016,2016.
[9] Ruffo Riccardo; Guglielmi Paolo (2016),”Simple parameters estimation and precise over-voltage simulation in long cable connected drives”, In: IECON16, 2016.
[10] Khalilian Mojtaba; Rosu Stefan George; Cirimele Vincenzo; Guglielmi Paolo; Ruffo Riccardo (2016), “Load identification in dynamic wireless power transfer system utilizing current injection in the transmitting coil”, In: Load identification in dynamic wireless power transfer system utilizing current injection in the transmitting coil, 2016.