TAKE HOME ASSIGNMENT

Propose and Simulate Thermal Models for EVs

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A Simplified Model for an EV Thermal Management System

Introduction

The goal of a thermal management system in an electric vehicle (EV) is to regulate the cabin air temperatures all the time at a comfortable temperature range 20 – 25°C. During the summer, this means having to cool the cabin air, and during the winter, it should heat it. It's also required to dissipate heat from the battery pack and the motor.

One of the best ways to achieve both goals is using a heat pump system that uses the heat from the battery pack and motor to heat the cabin. It can also be used in a different configuration to reject heat from them and the cabin to the environment during hot weather.

Configurations

1. <u>In Winter conditions</u>

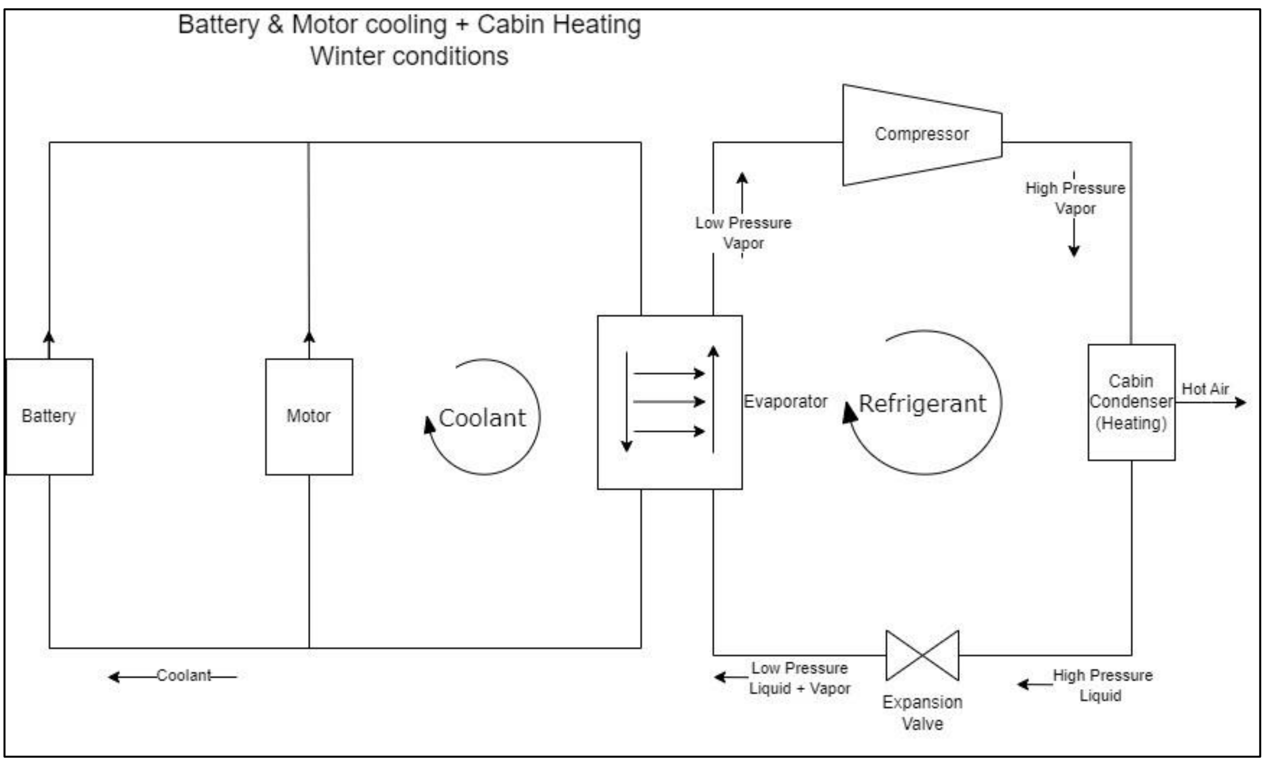


***Fig. 1** – Battery and Motor Cooling + Cabin Heating (Winter Conditions)*

The drawing above shows that the coolant absorbs the heat emitted from the Battery pack and the motor. This heat is then transferred to a refrigerant cycle to heat the cabin.

2. **In Summer conditions**

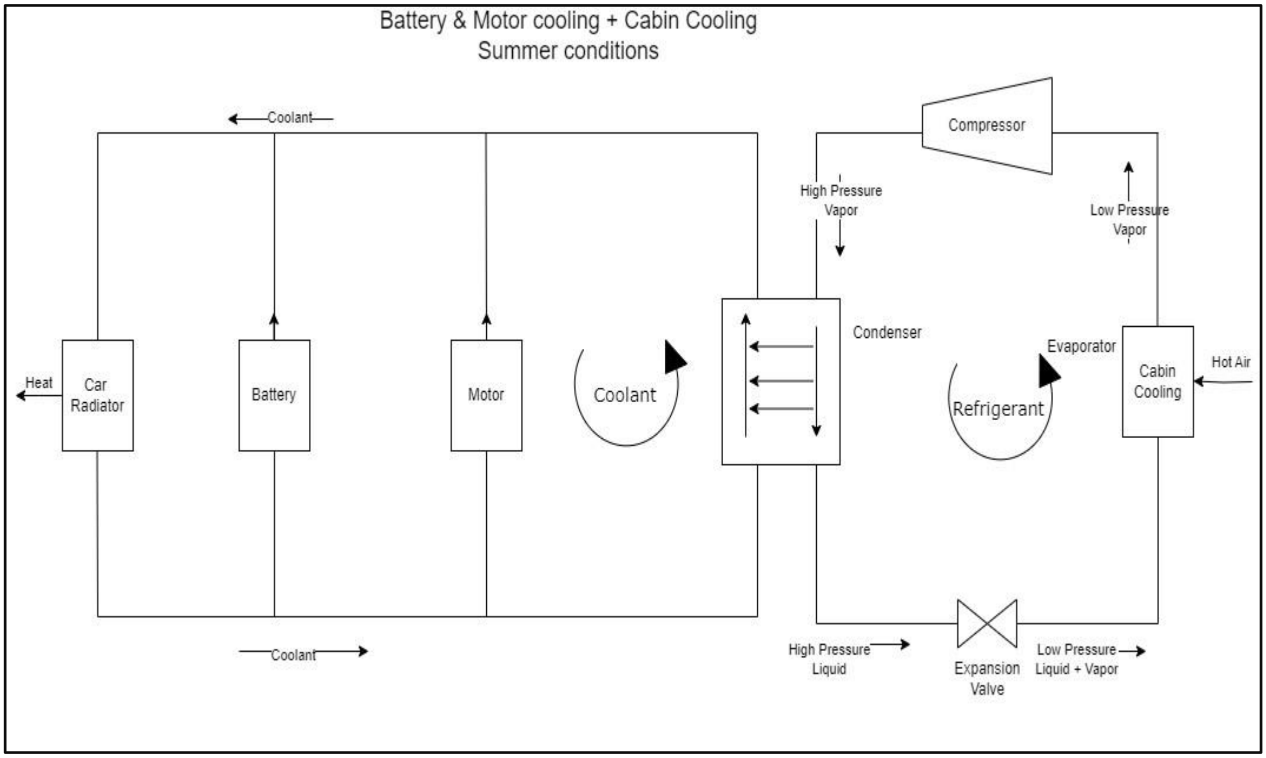


Fig. 2 – Battery and Motor Cooling + Cabin Cooling (Summer Conditions)

In this drawing, the refrigeration cycle is reversed, and it rejects heat to the coolant cycle, which in turn absorbs this heat and the heat energy coming from the battery and the motor. It rejects them into the environment using the car's radiator. We noticed that the car radiator was not used in the previous drawing because all the heat was directed at the cabin.

Assumptions

1. **Battery Heat generation:**

The heat generated by a battery can generally be assumed to be equal to the internal losses that happen inside it due to the current that passes through it. This can generally be calculated as

$$\boldsymbol{Battery\ Losses = I^2 * R_{int}}$$

where R_{int} is the internal resistance of the battery. We're now going to attempt to calculate these values.

To determine the current use of an electric vehicle, we need to know how much power is used on average. An average Tesla Model 3 car uses approximately 1kWh per 6km of driving [1]. Using the UDDS(FTP 75) drive cycle, the average velocity is 31.5km/h[2]. This means that the power consumption is approximately 5.25 KW. Using a nominal battery voltage of 350VDC, we get 15A of current.

We need to estimate the R_{int} of the battery pack. The internal resistance of a li-on cell varies according to many things, but we can estimate it around 70mΩ for one cell in average conditions [3]. We can estimate the whole pack as a huge network of series and parallel cells. It is worth noting that there will usually be additional losses due to the wiring between the cells. However, these are usually smaller in comparison and will not be calculated.

If we want our battery pack to be around 55kWh with 350V, using the 21700 cell specs (3.6-3.7V and 5000mAh), we find out that we need around 96 cells in series and 31 cells in parallel. Working out the total resistance of the pack to be approximately 0.217Ω.
Finally, we can now calculate the total battery losses to be -

$$\boldsymbol{Battery\ Losses = I^2 * R_{int} = 225 * 0.217 = 48.825 \approx 50W}$$

2. **<u>Motor losses:</u>**

In the last section, we calculated that the EV consumes 5.25KW on average. Most of that power actually goes to the motor. Therefore, by knowing the motor's efficiency, we can estimate how much it is producing. EV motors' efficiency is variable and depends on the torque and speed. However, they can generally be assumed to be around 90-95% efficient [4]. Using that number, we can approximate the losses to be 262.5 – 525W. We will use a number closer to the higher end of the spectrum and assume it to be 500W.

3. **<u>Cabin Thermal Load:</u>**

The cabin thermal load depends on many factors, such as the outside temperature, the number of passengers in the car, the car surface area and many other factors. We will calculate the load assuming 4 people are in the car and an average-sized EV, such as the model 3. We will also use weather data from California since it is one of the hottest places in the US. We will assume that the car is in the sun at 12 PM at noon. Using all these parameters and using Global Solar Atlas, we can extract the solar radiation data.

$$\boldsymbol{Q_{cabin} = Q_{met} + Q_{metal} + Q_{glass}}$$

Heat generated by the passengers Q_{met} is the heat generated by one human at rest multiplied by 4. From [5], we know that one human at rest generates 105W on average. Therefore

$$\boldsymbol{Q_{met} = 105 * 4 = 420W}$$

Heat transfer through the metal -

$$Q_{metal} = heat\ transfer\ coefficienct(Um) * Surface\ Area(Am) * \Delta T$$

Where ΔT is the temperature difference between the metal and the cabin.

Let's assume we want a cabin temperature of 25°C and outside temperature is 40°C in summer, the car's metal can be at 50°C because it's heating up from the sun. We can then assume ΔT to be 30.

We calculated the surface area of a car to be around 18 m^2 and obtained Um as 8 between steel and air.

Heat transfer between the glass and the cabin Q_{glass} consists of two parts, the first part is the convection like the metal and the other part is the solar radiation falling on it. It consists of direct radiation falling from the sun on the glass and the diffuse radiation (happens due to scattering of solar radiation when it hits air molecules). Using Global Solar Atlas, we obtain values for both radiations and then using equations.

$$Q_{dir} = I_{dir} * cos(\alpha) * Area * \tau$$
$$Q_{dif} = I_{dif} * Area * \tau$$

Where α in the angle between the sun and the glass and it is 60° at noon

Combining all these equations in one excel sheet (attached) for the ease of use and manipulations-

Glass Heat load(Qglass)	Value	Units
Heat Transfer Coefficient(Ug)	5	W/m²K
Surface Area(Ag)	2.5	m²
Difference in Temperature(ΔTg)	25	K
Direct Radiation(Idiff)	177	W/m²K
Diffuse radiation(Idir)	1000	W/m²K
Incidence Angle(I)	1.047197551	rad
Transmissivity(tau)	0.8	
Qglass	1666.5	W

Metal Heat Load(Qmetal)	Value	Units
Heat Transfer Coefficient(Um)	8	W/m²K
Surface Area(Am)	18	m²
Difference in Temperature(ΔTm)	30	K
Qmetal	4320	W

Metabolic Heat Load(Qmet)	Value	Units
Number of passengers	4	
Human avg heat production	105	W
Qmet	420	W

Total heat load	6406.5

Table 1 *– Heat Load Calculation*

We can easily change conditions or assumptions and see the effect without having to repeat the calculation.

Diagrams/Schematics and Model

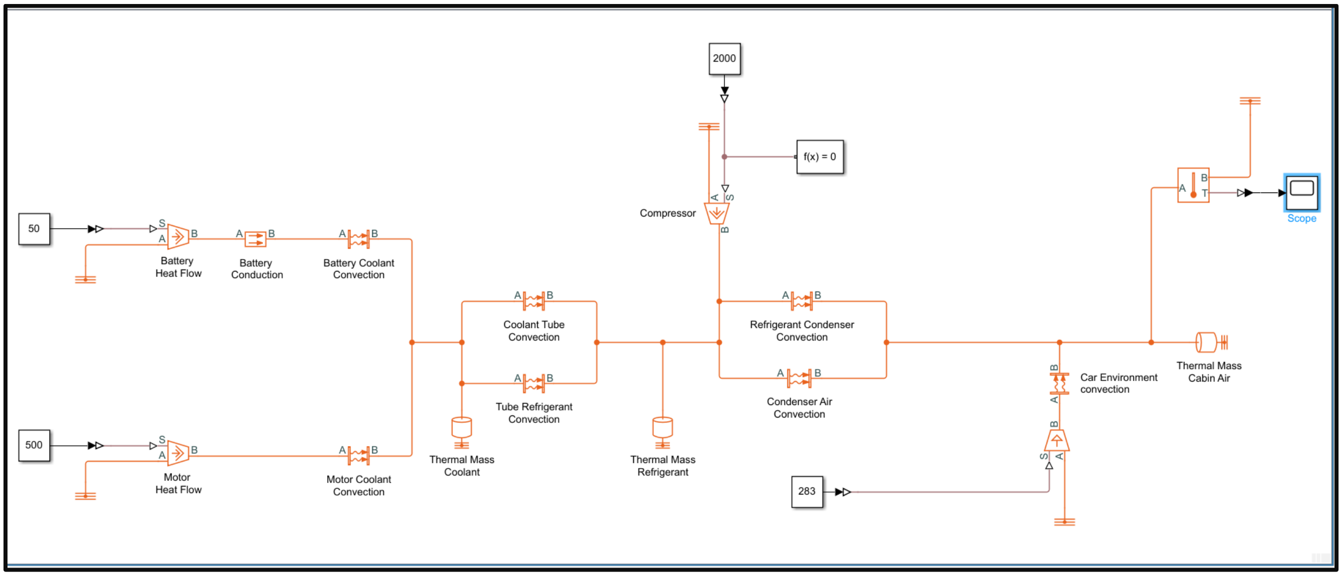


Fig. 3 – Winter conditions 1D thermal model

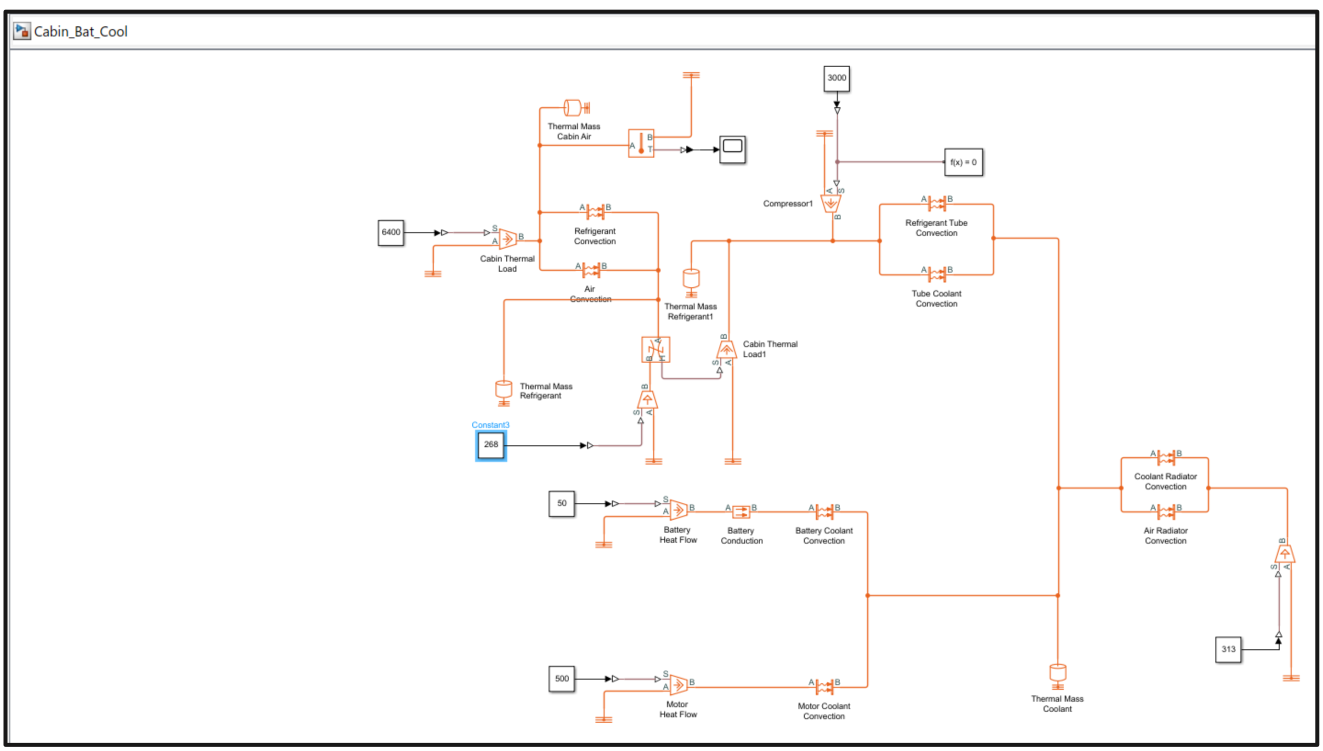
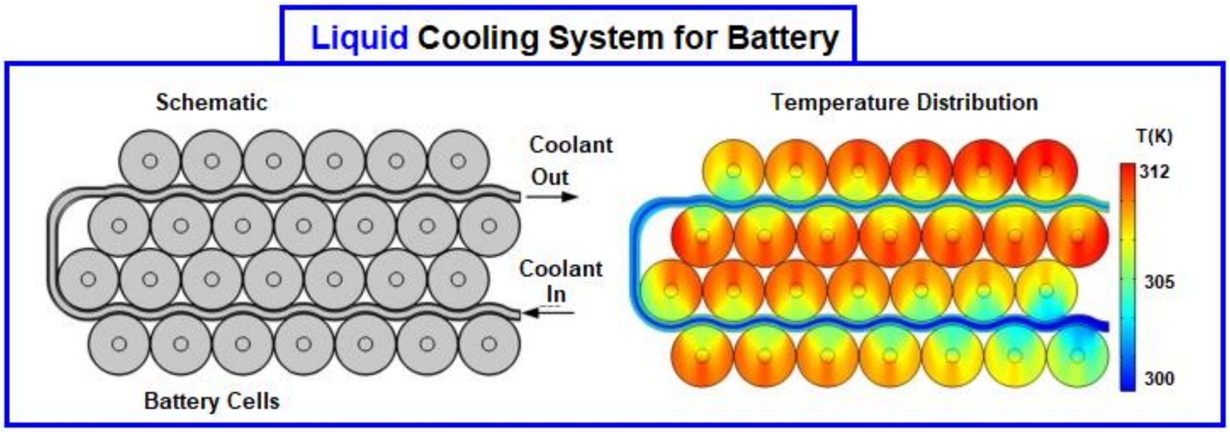


Fig. 4 – Summer conditions 1D thermal model

Calculating the heat transfer parameters

Let's start by calculating the conduction parameters for the battery conduction.

The needed parameters are the thickness of the conducting material, its thermal conductivity, and the surface area.



The coolant goes through a tube looking like this in between the cell. This means that the thickness will be approximately the cell diameter (18mm), the thermal conductivity will be that of the cell itself (15 W/ (m*K)). The area is a little bit more complicated to get, looking at the illustration above, we see that each two strings of parallel cells have one coolant tube going between them.

$$\boldsymbol{Area = No.of\ tube\ loops * cell\ height(tube\ width) * pack\ length}$$

Knowing that in our battery we should have 31 parallel strings, we can say that the cooling tube loops 16 times around the cells. Multiplying that by the cell height and pack length of an average EV we get an area of $5.33m^2$.

Calculating the convection heat transfer coefficient is a complex calculation that uses the tube dimensions, coolant flow rate (assumed to be 25LPM taken from Tesla) and coolant fluid properties (assumed to be 50/50 water glycol mixture). We used an excel sheet to perform this calculation as we repeated it several time in the model for different heat transfer processes (radiator, cabin condenser…etc.). The excel sheet containing this calculation for all the components will be attached.

Parameter	Value	Unit		Intermediate Variable	Value	Unit
Coolant Flowrate	25	LPM				
Tube Area	0.00054	m^2		Coolant Velocity(V)	0.771606	m/s
Hydraulic Diameter (Dh)	0.01125	m				
Kinematic Viscosity	0.000000733	m^2/s		Reynolds Number(Re)	11842.53	
Thermal conductivity(k)	0.415	W/m K		Nusselt Number(Nu)	51.74393	
Heat Transfer Coefficient(h)	**1908.776145**					

***Table 2** – Heat Transfer Coefficient Calculation*

Results

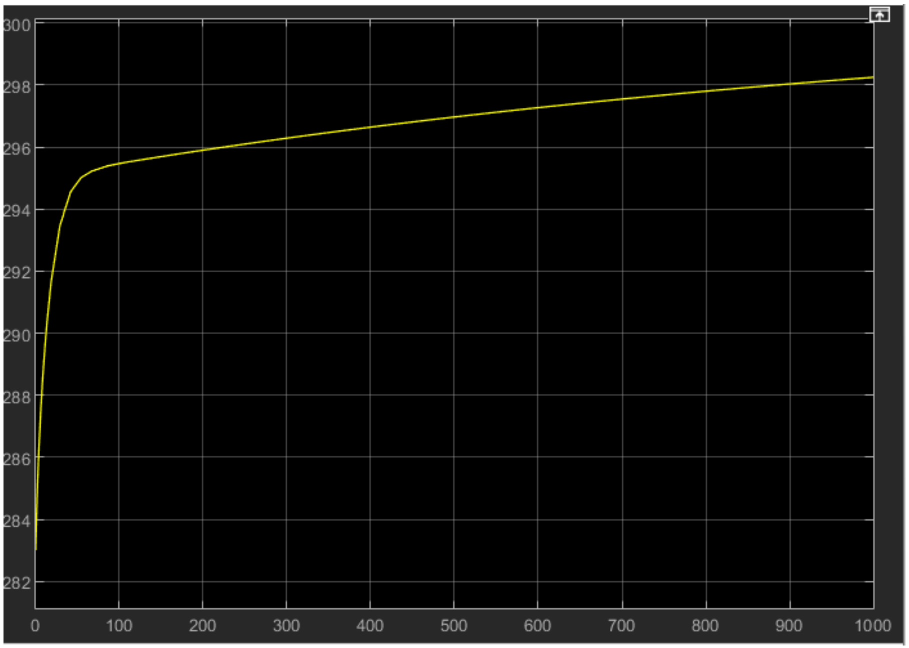


***Fig. 5** – Winter conditions Car Cabin Temperature in Kelvin(K)*

Temperature starts at 10°C(283°K) and reached above 25°C (298K). It's worth noting that this model has no control system to turn on and off the AC.

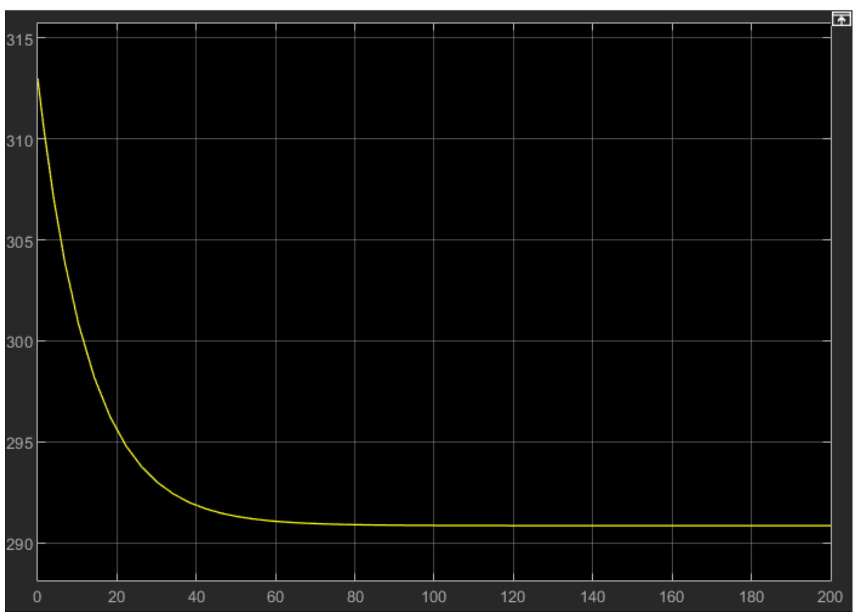


***Fig. 6** – Summer conditions Car Cabin Temperature in Kelvin(K)*

Temperature starts at 40°C(313°K) and reached above 18°C (291K).

References

[1] “European Union Energy Label: Tesla Support Other Europe,” Tesla, https://www.tesla.com/en_eu/support/european-union-energy-label (accessed Mar. 31, 2024).

[2] “US: Light-duty: FTP-75,” Transport Policy, https://www.transportpolicy.net/standard/us-light-duty-ftp-75/ (accessed Mar. 31, 2024).

[3] L. Chen et al., “Estimation the internal resistance of lithium-ion-battery using a multi-factor dynamic internal resistance model with an error compensation strategy,” Energy Reports, vol. 7, pp. 3050–3059, Nov. 2021. doi: 10.1016/j.egyr.2021.05.027

[4] R. Thomas, H. Husson, L. Garbuio, and L. Gerbaud, “Comparative study of the tesla model S and Audi e-tron induction motors,” 2021 17th Conference on Electrical Machines, Drives and Power Systems (ELMA), Jul. 2021. doi:10.1109/elma52514.2021.9503055

[5] “Ambient Environment: Thermal Conditions,” Thermal conditions lecture, https://ergo.human.cornell.edu/studentdownloads/DEA3500notes/Thermal/thregnotes.html (accessed Mar. 31, 2024).