Motor Cooling System Design

Organiser : Automobile Club

Kriti 2025

Final Submission Report

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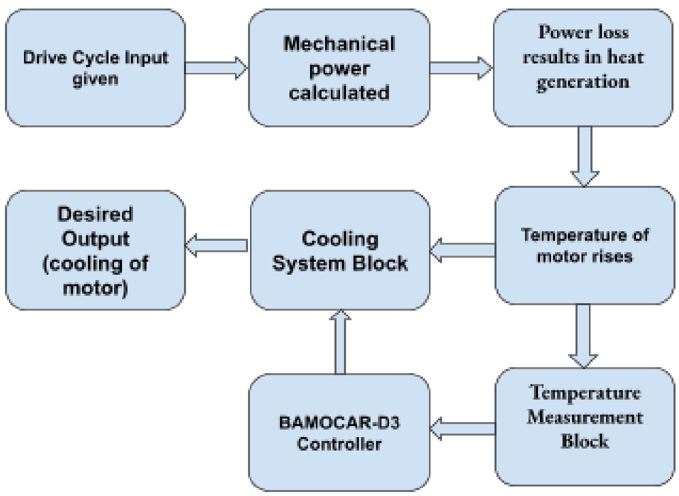
1. Abstract

For Formula Student electric vehicles, achieving high performance and efficiency is a primary goal. However, one of the critical challenges in their design is managing the heat generated by the motor and motor controller during high-speed operation over extended periods. If excessive heat is not effectively managed, it can significantly impact motor efficiency, reduce the motor's lifespan, and cause performance issues or even failures during races. Therefore, an effective thermal management system is essential to ensure consistent performance and reliability throughout the race.

2. Problem Understanding

In Formula Student electric vehicles, maintaining optimal motor temperature is essential for ensuring performance, efficiency, and reliability. The **EMRAX 208** motor and **BAMOCAR-D3** controller generate significant heat during prolonged high-speed operation, which, if not managed effectively, can lead to thermal degradation, reduced efficiency, and potential system failures. The challenge lies in developing a compact, lightweight, and energy-efficient cooling system that can dynamically regulate temperature under varying drive cycles while adhering to constraints such as coolant type, flow rate limits, and a **12V power supply** for **pumps and fans**. A well-designed cooling strategy must effectively dissipate heat, optimize coolant circulation, and minimize power consumption, ensuring the motor operates within its **safe temperature range** of **25°C to 45°C** without compromising vehicle performance.

3. Cooling Architecture



The problem statement requires us to use a given drive cycle which gives us the inputs of the motor . Hence, for a specific rotation of the motor and torque generated , there is some heat generated due to the power loss . This has been given to us by the **EMRAX 208** map which gives us the efficiency contours along with corresponding angular speed and torque of the motor. Now with the heat generated we can find the rise in temperature and so we now aim to reduce this temperature to **below 45°C**. The temperature measurement block gives the temperature input to the **BAMOCAR-D3** controller which then helps **reduce overheating.** It adjusts these parameters based on real-time feedback from the motor, such as temperature and load, and sends the necessary adjustments to the cooling system.

Hence , the motor is cooled and we get the temperature within the desired range.

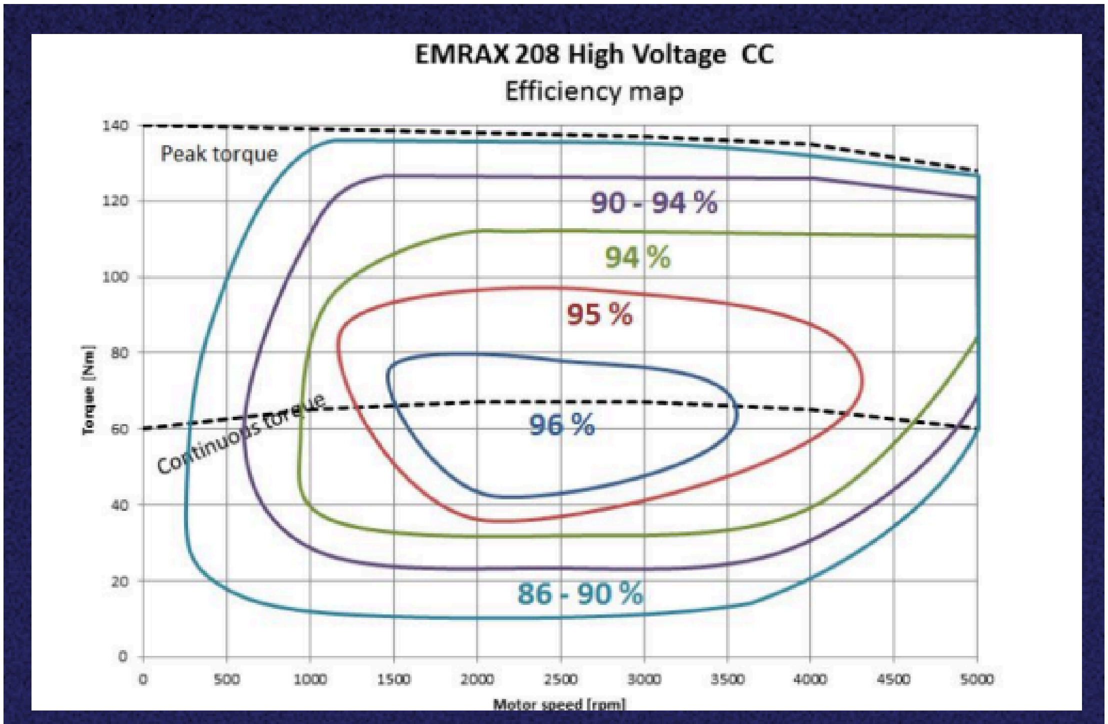


Fig1 Efficiency map of EMRAX 208

3.1 Cooling Strategies:

Objectives :

The primary objective of this cooling system is to regulate the motor and motor controller temperature while ensuring efficient heat dissipation.

The working principles of the cooling system:

- **Heat Absorption:** Heat generated by the motor and motor controller is transferred via metal interfaces (pipes).
- **Coolant Circulator:** A water pump circulates the heated coolant from the motor to the radiator. The flow rate is controlled to ensure maximum heat transfer efficiency.

- **Heat Dissipation:** The radiator removes heat from the coolant and the fan forces the air through the radiator to enhance cooling efficiency.
- **Coolant Storage & Recirculation:** A coolant tank holds excess coolant and compensates for thermal expansion. The cooled water is then recirculated back to the motor, maintaining a stable operating temperature.

Coolant flow optimization:

- Maintaining an optimal flow rate ensures that the coolant absorbs enough heat without excessive energy consumption.
- **Avoiding excessive flow rates** prevents unnecessary pump power usage and **reduces system inefficiencies.**
- Flow rate is adjusted using Simulink-based control algorithms taking help of the **BAMOCAR-D3** to dynamically regulate cooling performance.

Radiator Efficiency Cooling:

- The radiator size and material are **optimized for maximum heat dissipation**.
- **Aluminum radiators** are preferred due to their **high thermal conductivity**.

Fan-Assisted Cooling:

- The fan speed is varied based on cooling demand to **optimize energy efficiency**.

Heat Transfer Enhancement:

- Coolant pipes are made of **thermally conductive** materials (e.g. aluminum) to minimize heat loss.

Temperature Monitoring & Control:

- Sensors measure real-time coolant temperature at different points (motor, before & after radiator).
- A control system adjusts pump and fan speeds to maintain an optimal temperature range.

4. Assumptions and Justification

4.1 Assumption

- We have assumed the **specific heat** of motor to be **350 J/(kg*K)**.
- Heat generated = inefficiencies in the motor and controller.
- **Ambient air** temperature is **fixed at 25°C**.
- Maximum motor temperature should not **exceed 45°C**.
- Coolant flow rate should be within manufacturer limits.

4.2 Justification

Justification of Cooling System Approach:

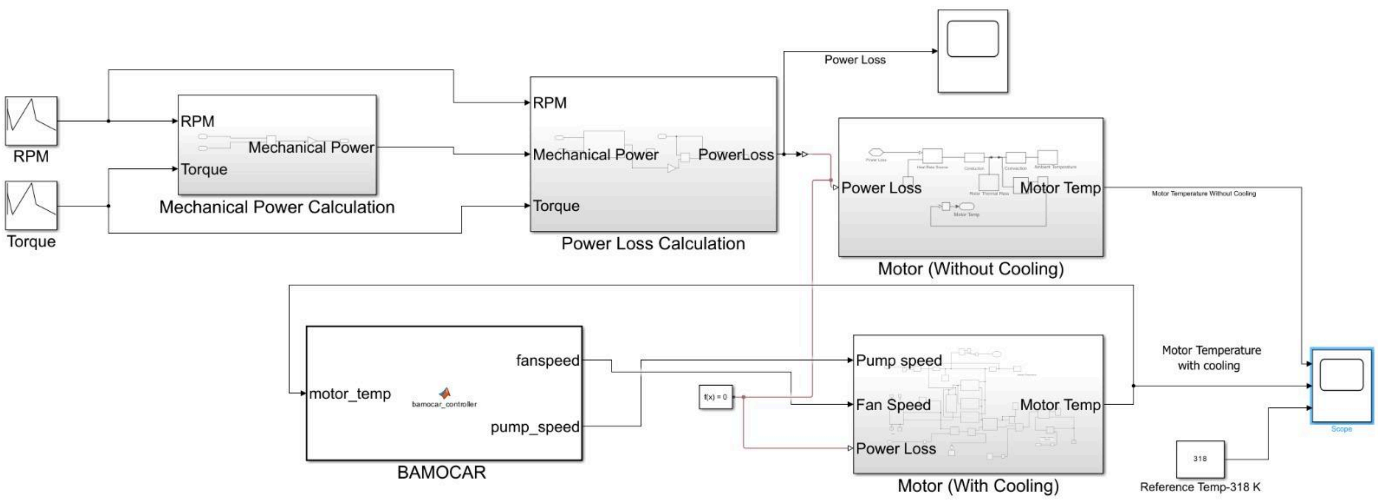
Several cooling strategies were analyzed, including

1. **Air Cooling:**
    - Simple, lightweight, and inexpensive
    - However, this was found to be insufficient for high- power motors like EMRAX 208 due to limited heat dissipation.
2. **Liquid Cooling (Water):**
    - More efficient in heat transfer than air.
    - Can regulate motor and controller temperature more effectively in prolonged racing conditions.

- Requires a pump, radiators and a closed- loop system.

Given these options, **liquid cooling** was chosen due to its **superior thermal conductivity** and heat capacity, making it ideal for high performance.

5. System Breakdown



5.1 Mechanical Power Calculation

The mechanical power required for the motor is calculated from the rpm and torque from the drive cycle.

Motor Power Calculations (Mechanical Power Output)

Mechanical power describes the output power that moves the object attached to the motor. It is simply defined as speed times torque (the rotational equivalent of a linear force).

$$P_{out} = \tau * \omega$$

Where:

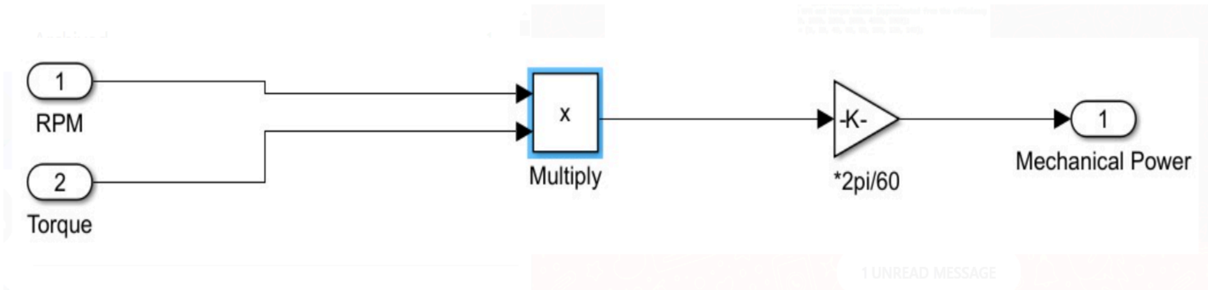
P_{out}=Output power (W)
t=Torque (Nm)
w=Angular speed (rad/s)

The angular speed of the motor can be estimated if designers know the rotational speed of the motor, as shown in the equation below:

$$\omega = \frac{2\pi N}{60}$$

Where:

N=Rotational speed (rpm)



The above diagram represents how the mechanical power calculation is implemented in Simulink.

5.2 Power Loss Calculation

The power loss generated in the motor is what is converted into heat in the system. In order to find the power loss we first find the efficiency of the motor at the particular time from the input rpm and torque. We use the efficiency map of the EMRAX 208 in the MATLAB function block to find the efficiency.

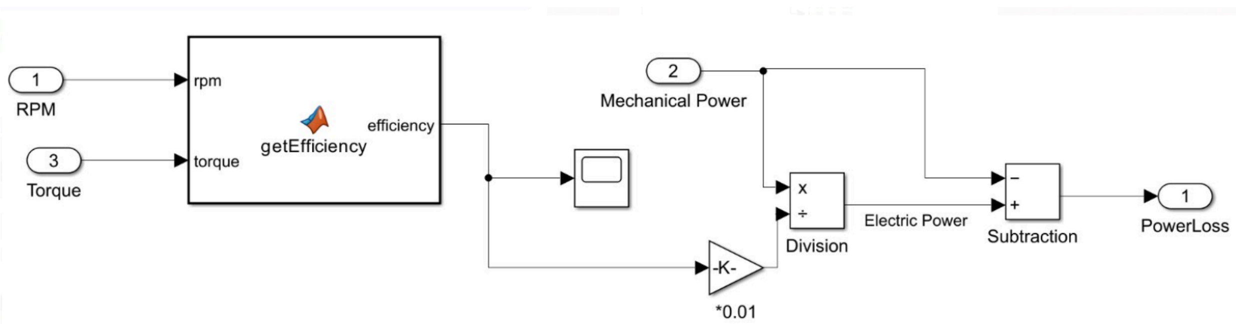
```
function efficiency = getEfficiency(rpm, torque)
    % Define known RPM and Torque values (approximated from the efficiency map)
    rpm_values = [0, 1000, 2000, 3000, 4000, 5000];
    torque_values = [0, 20, 40, 60, 80, 100, 120, 140];

    % Efficiency map (approximated from the image)
    efficiency_map = [
        85  86  87  88  89  90;
        87  88  89  90  91  92;
        89  90  92  94  95  94;
        90  92  94  96  95  93;
        88  91  94  95  94  92;
        87  89  92  94  93  91;
        86  88  90  92  91  90;
        85  87  89  90  89  88
    ]; % Rows correspond to torque_values, columns to rpm_values

    % Interpolation to estimate efficiency for given RPM and Torque
    efficiency = interp2(rpm_values, torque_values, efficiency_map, rpm, torque, 'linear');

    % Ensure efficiency is within reasonable bounds
    efficiency = max(85, min(96, efficiency)); % Efficiency in range 85-96%
end
```

After finding the efficiency of the system, we find the electric power generated by the motor.

$$\eta = \left(\frac{\text{Mechanical Power}}{\text{Electric Power}}\right) \times 100$$

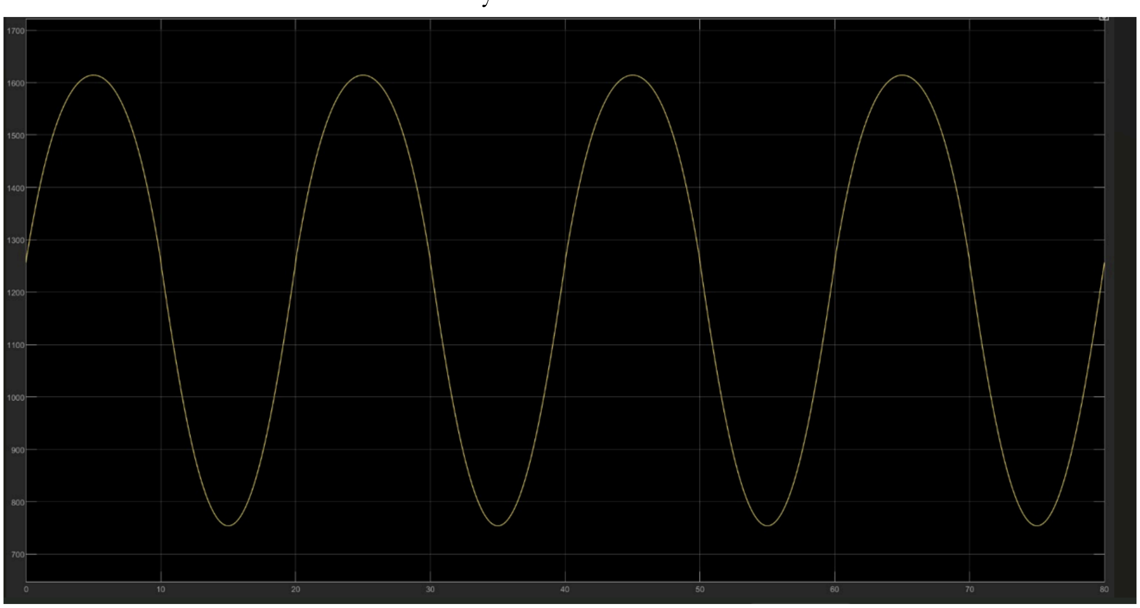
The power loss generated in the system is given by

Power Loss=Electric Power-Mechanical Power



Power Loss Calculation Subsystem

Another interesting observation we noticed was that the power loss follows a sine wave for the duration of the drive cycle.



5.3 BAMOCAR- D3 Controller:

We used BAMOCAR- D3 Controller to take motor temperature as input and find the required speed of pump and fan. The controller sets the speed of the pump and fan to maximum when the motor temperature is greater than **318.15 K (45°C)** and turns off the cooling system when motor temperature is less than **298.15 K (25°C)**. When the motor temperature is in between the maximum and minimum temperature the fan and pump speed is controlled using a linear function.

Maximum Pump Flow Rate - 8L/min

Maximum Fan Speed (Air flow) - 20 m/s

```
function [fanspeed, pump_speed] = bamocar_controller( motor_temp)
    % Example Parameters
    max_temp = 318.15; %Kelvin
    min_temp = 298.15; % Kelvin
    % Control Logic
    if motor_temp > max_temp
        fanspeed=262.87;
        pump_speed = 0.0001333; % Max cooling
    elseif motor_temp < min_temp
        fanspeed = 0;
        pump_speed = 0; % Minimal cooling
    else
        fanspeed = ((motor_temp - min_temp) / (max_temp - min_temp))*262.87;
        pump_speed = ((motor_temp - min_temp) / (max_temp - min_temp))*0.000099975;
    end
end
```

BAMOCAR - D3 Controller Function

5.4 Cooling System

The power loss generated within the system is converted into heat in the motor. The motor, with a thermal mass of **9.1 kg** (as stated in the datasheet), experiences a rise in temperature due to this heat. Heat is dissipated through conduction and convection, leading to an decrease in motor temperature. To maintain the motor's temperature below **318.15 K (45°C)**, a cooling system is designed to regulate and control this heat buildup.

5.4.1 Cooling System Components and Sensors:

Tank: Stores and supplies the **liquid coolant (water)** to the system.Pump: Controls the flow rate of the coolant as per the settings defined by the BAMOCAR-D3 Controller.

Radiator (Heat Exchanger): Transfers heat from the hot water coming from the motor to the surrounding air, cooling the water before it returns to the motor.

Fan: Blows cold air into the radiator to assist in the cooling process. The fan speed is controlled through an angular velocity source, which is managed by the BAMOCAR-D3 Controller.

Pipes: Facilitate the circulation of coolant by connecting the motor, radiator, and tank, ensuring that cold water is delivered to the motor and hot water is returned to the tank.

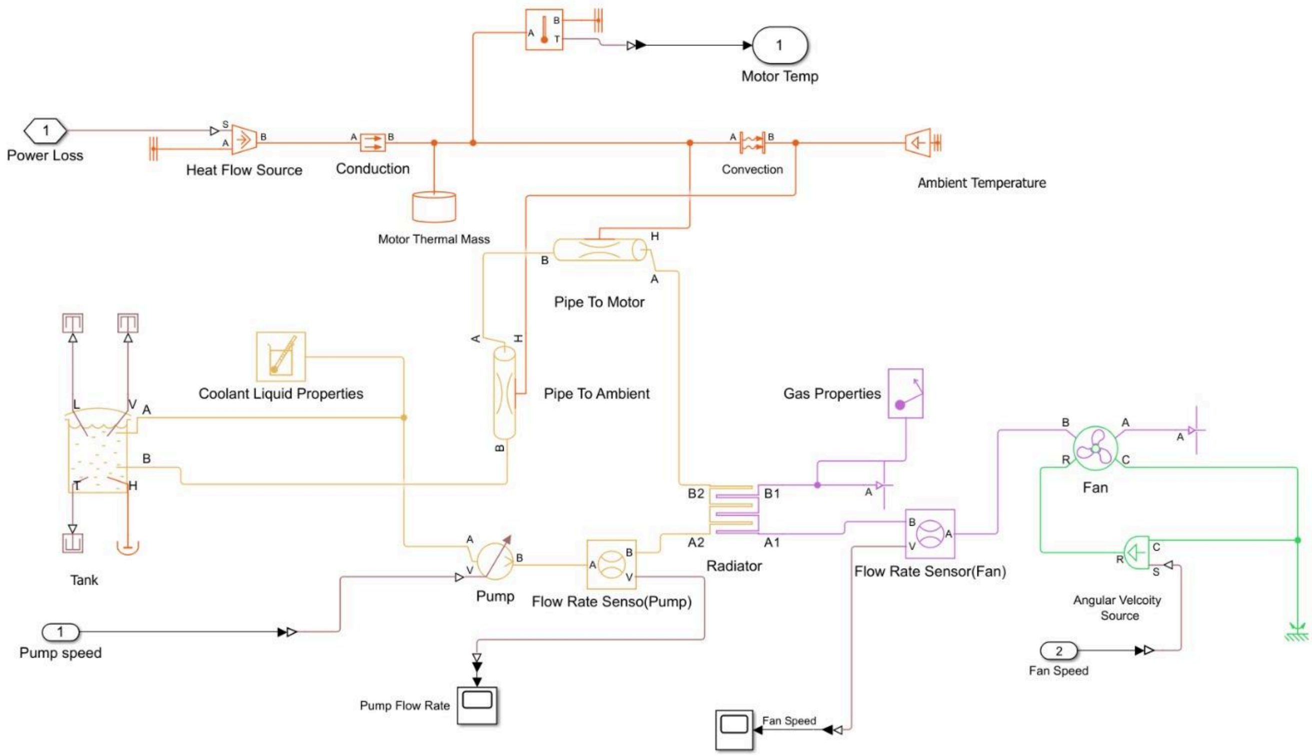
Temperature Sensor: Tracks the temperature of the motor over time.

Volume Flow Rate Sensor (Liquid): Measures the volume flow rate of the water coolant.

Volume Flow Rate Sensor (Gas): Measures the volume flow rate of air through the system.

5.4.2 Cooling System Design

Approach 1:



We have designed the system with a single pipe from the radiator to the motor and another pipe connecting the motor back to the tank. The dimensions for the two pipes is as follows:

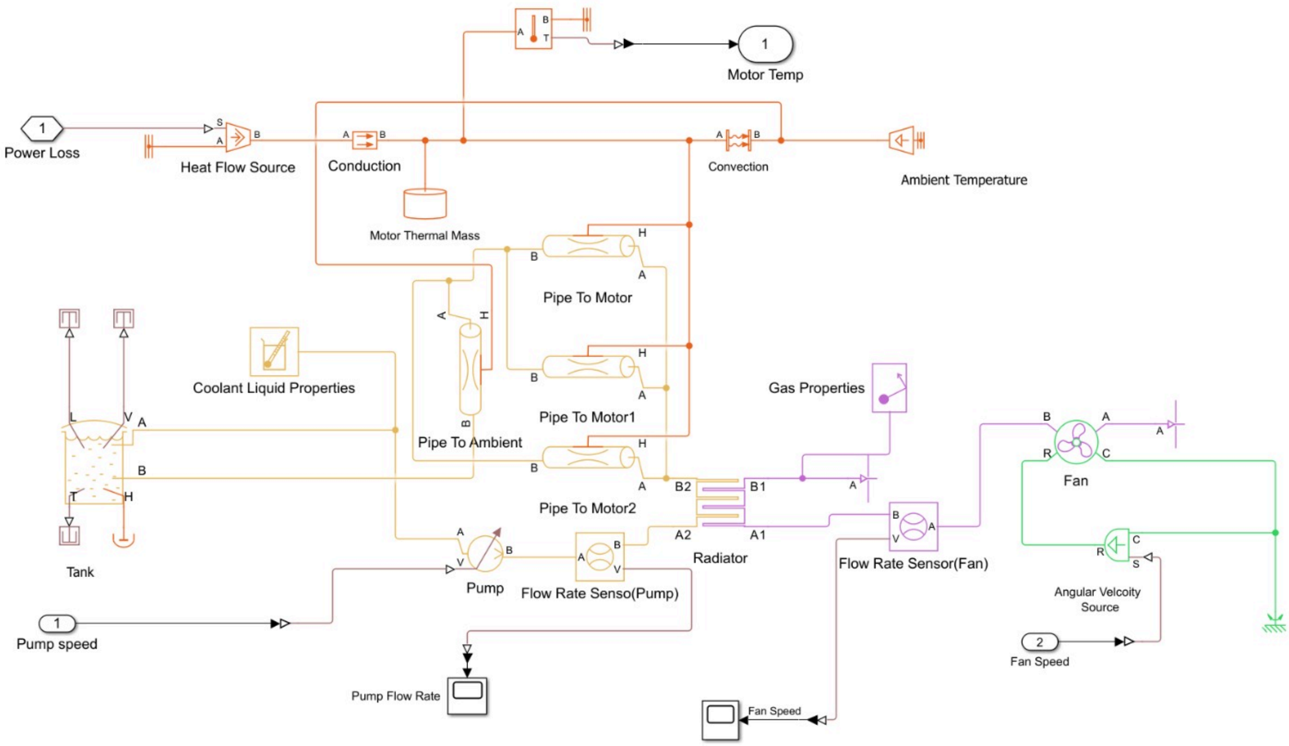
Pipe 1 (Radiator to Motor) : Length = **50 cm**

Diameter = **30 cm**

Pipe 2 (Motor to Tank) : Length = **50 cm**

Diameter = **30 cm**

Approach 2:



We have designed this system with three pipes connected in parallel between the radiator and the motor and a single pipe connected between the motor and tank. The dimensions of each pipe are as follows:

Pipe 1 (Radiator to Motor) * (3 such pipes) : Length = **50 cm**

Diameter = **13 cm**

Pipe 2 (Motor to Tank) : Length = **50 cm**

Diameter = **22 cm**

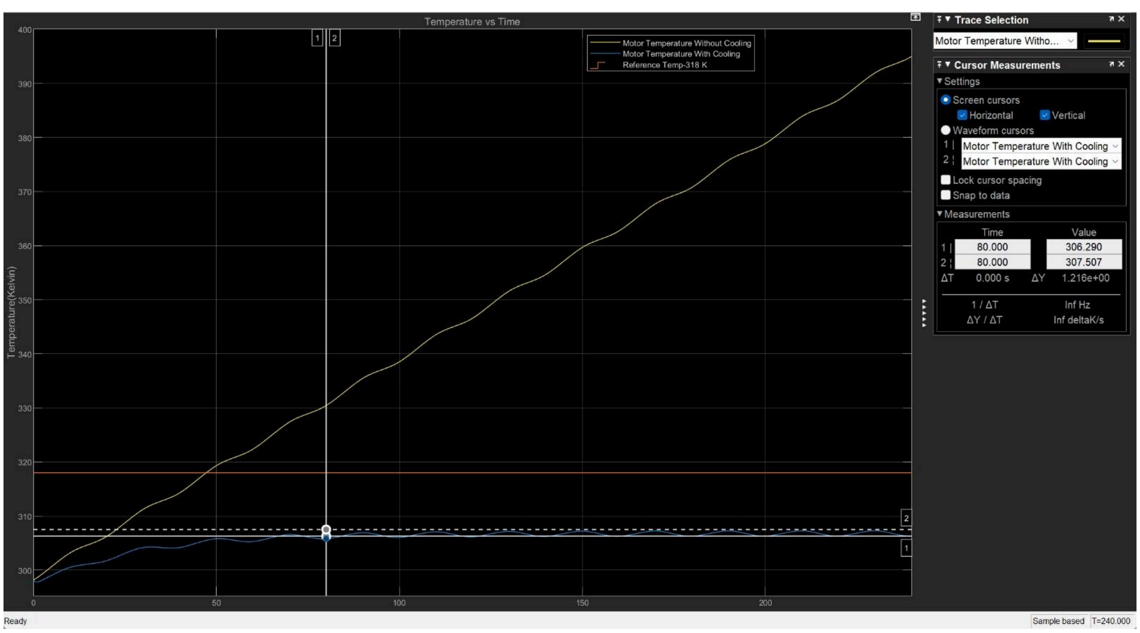
5.4.3 Cooling Mechanism:

A **liquid cooling (LC)** system is used to maintain the motor's temperature within a safe operating range. The pump circulates coolant to the radiator, where the water is cooled through heat exchange with the air. The cooled water is then returned to the motor, where it absorbs heat. The heated water is then pumped back to the radiator, and the cycle repeats. This system relies on the thermal properties of the coolant and pipes to effectively regulate the motor temperature.

6. Results

We have implemented two model solutions to cool the motor, so we would be discussing the results obtained separately. The output obtained is as shown in the below figure where the **Red line** signifies the **45°C mark** , the **yellow graph** represents the temperature of the motor **without cooling** and the **blue graph** represents the temperature of the motor **with cooling**. As we can see, our cooling solution ensures that the temperature of the motor with cooling(**Blue Graph**) always remains below the upper limit of **45°(Red line).** Without cooling we can see the temperature of the motor(**Yellow Graph**) keeps on shooting up and exceeds our thresholds. We can also note that in both methods, the temperature of the motor saturates within **80s** approximately,

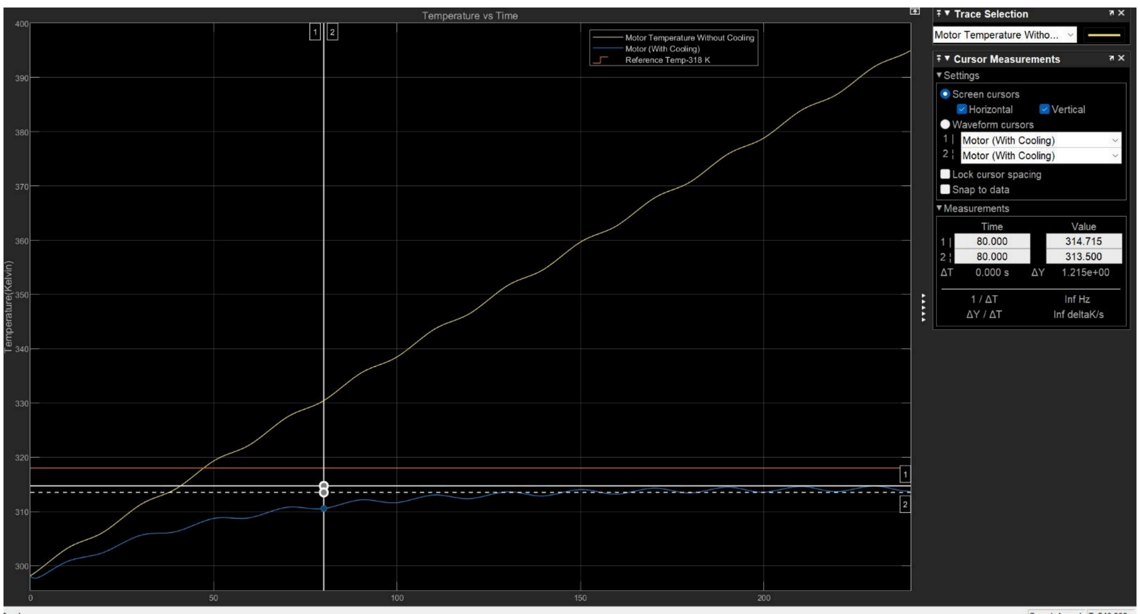
Approach 1:



In the first approach we had used pipes of **30 cm diameter** and **length 50 cm** for the transportation of the coolant to the motor from the fan . We can see that the temperature of the motor saturates near **308K (35°C)**

Approach 2:

In this approach we optimized the cooling system by adding more pipes in parallel and increased the efficiency of the system. For the simulation of **240 seconds**, the motor temperature is found to saturate near **315 K(42°C)**



7. CBOM (Costed Bill of Materials)

CBOM REPORT FOR APPROACH 1

Serial No	Item	Description	Quantity	Unit Price (in dollars)	Total Price (in dollars)	References For Prices
1	EMRAX 208 Motor	High performance electric motor	1	4500 to 5500	4500 to 5500	https://www.indiamart.com/proddetail/emrax-208-motor-86kw-150nm-2854304363930.html?srsltid=AfmBOorOucQ6m25s6ltI43g6Y65Hu-kM5UaoJpdf1V-6Wjq8eNIHzBZq
2	BAMOCAR-D3	Digital battery motor controller	1	4500 to 5500	4500 to 5500	Standard Price
3	Liquid Cooled Radiator	Performance Auxiliary Radiators	4	525	2100	https://www.mishimoto.com/performance-auxiliary-radiators-bmw-g8x-m3-m4-2021.html
4	Cooling Fan	Performance Fan Shroud Kit	1	300 to 380	300 to 380	https://www.mishimoto.com/bmw-e36-performance-fan-shroud-kit-1992-1999.html
5	Temperature Sensor	NTC thermistor to measure temperature of motor	1	10 to 15	10 to 15	https://www.mouser.com/c/circuit-protection/thermistors/ntc-thermistors/?srsltid=AfmBOop96l1zRqeazN1WPVbCPGe4H7g5qv-taVIzLuaE8794sOcbrwOi
6	Pipe	6061-T6 aluminium pipe (with a hydraulic diameter of 90mm).	2	10 to 20 for each half meter pipe	20 to 40	The price typically ranges from $20 to $40 per meter, influenced by material quality, supplier markup, and shipping costs.
7	12V Low Power Supply	Constant DC Voltage Source for Pump and Fan	1	25	25	https://a.co/d/9oCyAHt
8	Pump	Mishimoto 12V Electric Water Pump	1	300	300	https://www.mishimoto.com/bmw-n52-water-pump-06-12.html
9	Tank	Aluminium Reservoir	1	90	90	https://www.mishimoto.com/aluminum-coolant-reservoir-tank.html
10	Electrical Wiring	Connections between components of the control system	NA	NA	50	NA
11	Mounting Brackets and misc.	Fuses , small components , etc	NA	NA	50	NA

CBOM REPORT FOR APPROACH 2

Serial No	Item	Description	Quantity	Unit Price (in dollars)	Total Price (in dollars)	References For Prices
1	EMRAX 208 Motor	High performance electric motor	1	4500 to 5500	4500 to 5500	https://www.indiamart.com/proddetail/emrax-208-motor-86kw-150nm-2854304363930.html?srsltid=AfmBOorOucQ6m25s6ltI43g6Y65Hu-kM5UaoJpdf1V-6Wjq8eNIHzBZq
2	BAMOCAR-D3	Digital battery motor controller	1	4500 to 5500	4500 to 5500	Standard Price
3	Liquid Cooled Radiator	Performance Auxiliary Radiators	4	525	2100	https://www.mishimoto.com/performance-auxiliary-radiators-bmw-g8x-m3-m4-2021.html
4	Cooling Fan	Performance Fan Shroud Kit	1	300 to 380	300 to 380	https://www.mishimoto.com/bmw-e36-performance-fan-shroud-kit-1992-1999.html
5	Temperature Sensor	NTC thermistor to measure temperature of motor	1	10 to 15	10 to 15	https://www.mouser.com/c/circuit-protection/thermistors/ntc-thermistors/?srsltid=AfmBOop96l1zRqeazN1WPVbCPGe4H7g5qv-taVIzLuaE8794sOcbrwOi
6	Pipe	25 cm Diameter 13 cm Diameter	1 3	20 to 30 12.5 to 20	20 to 30 37.5 to 60	The price of 6061-T6 aluminium pipe typically ranges from $20 to $40 per meter, depending on factors such as material quality, supplier markup, and shipping costs.
7	12V Low Power Supply	Constant DC Voltage Source for Pump and Fan	1	25	25	https://a.co/d/9oCyAHt
8	Pump	Mishimoto 12V Electric Water Pump	1	300	300	https://www.mishimoto.com/bmw-n52-water-pump-06-12.html
9	Tank	Aluminium Reservoir	1	90	90	https://www.mishimoto.com/aluminum-coolant-reservoir-tank.html
10	Electrical Wiring	Connections between components of the control system	NA	NA	50	NA
11	Mounting Brackets and misc.	Fuses , small components , etc	NA	NA	50	NA

8. References

[1] Video 1:- Motor Cooling System | Simscape Essentials for Automotive Student Teams
[2] EMRAX 208 Datasheet:- emrax_208_technical_data_4.5.pdf
[3] BAMOCAR- D3 Datasheet:- BAMOCAR-PG-D3-700-400_EN.pdf