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Electric Vehicle Motor Cooling System Modelling Using Matlab Simscape

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Abstract: This study has efficient thermal management of electric vehicle (EV) motors is essential for ensuring optimal performance, reliability, and service life. This study models and simulates an EV motor cooling system using MATLAB Simscape, incorporating critical components such as the motor, cooling channels, pump, radiator, and thermal sensors. The model captures the heat generation and dissipation dynamics within the motor under realistic operating conditions. Both passive and active cooling strategies are analyzed across varying load and ambient conditions to evaluate thermal response and efficiency. Leveraging Simscape's multi-domain capabilities, the study integrates thermal, fluid, and mechanical subsystems to enable system-level analysis. Simulation results highlight the influence of flow rate, coolant properties, and ambient temperature on motor temperature regulation. The developed model provides a robust platform for optimizing EV motor cooling designs, minimizing thermal stress, and enhancing overall energy efficiency.

***Index Terms* - Thermal Ports, Heat Transfer, Coolant Loop, Pump, Fan, Fluid Properties, Driving Cycle, Motor Losses, Temperature.**

I. INTRODUCTION

As vehicle efficiency continues to improve, thermal management systems play an increasingly vital role in the effective design of both heavy- and light-duty vehicles. Understanding thermal trade-offs at the system level is essential for the development of advanced electrified traction drive systems. To support this, there is a critical need for flexible, scalable, and cost-effective modeling tools that can evaluate this trade-offs and inform the design of integrated thermal control strategies.

During vehicle operation, the air conditioning (A/C) system represents the largest auxiliary load in conventional vehicles. In light-duty vehicles in the United States, A/C systems are responsible for consuming over 5% of the total annual fuel usage [1]. This significant energy demand highlights the importance of optimizing thermal management and auxiliary load efficiency, particularly in the context of vehicle electrification.

Climate control loads have an even more pronounced impact on the performance of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs). For instance, HEVs can experience up to a 22% reduction in fuel economy when the air conditioning system is in use [2]. In EVs, the impact is often more severe, as cabin heating is challenged by the lack of waste heat typically available in internal combustion engines. Additionally, cooling the cabin can consume a substantial portion of the battery's energy, significantly reducing overall vehicle efficiency and driving range. Therefore, selecting an appropriate electric motor cooling method is critical and should be based on the motor's classification, power rating, and operating environment [3].

In all-electric vehicles (EVs), climate control systems can have an even greater impact on overall performance. Unlike conventional vehicles, EVs lack abundant waste heat from an internal combustion engine, making cabin heating particularly challenging. Moreover, cabin cooling can draw a significant portion of the available battery energy, leading to a noticeable reduction in vehicle efficiency and driving range.

Liquid cooling is a widely used and effective heat transfer method for high-power, enclosed electric motors. In a conventional configuration, the system comprises a pump, radiator, and a network of hoses. The circulating coolant absorbs heat generated by the motor and transfers it to the radiator, where it is dissipated to the surrounding environment, thereby maintaining optimal motor operating temperatures.

Air cooling is straightforward and features a simple structural design; however, its cooling performance may be insufficient for high-power applications. Additionally, the cooling fan is typically coupled to the motor shaft, leading to parasitic energy losses and limited controllability. In contrast, liquid cooling offers superior thermal performance but incurs additional energy consumption due to the operation of the coolant pump and radiator fan.

On the other hand, liquid cooling introduces additional weight and system complexity due to the inclusion of coolant lines and associated components. Heat pipes, which can operate passively in the presence of a temperature gradient, offer an alternative or supplementary cooling solution. However, their heat transfer capacity is limited by factors such as the capillary limit, working fluid properties, and operating temperature range. Integrating heat pipes into the system can help offload part of the thermal load from the liquid cooling loop, potentially reducing overall energy consumption and improving system efficiency [4].

II. PROBLEM STATEMENT

An innovative cooling system combining heat pipes and circulating liquid was designed and simulated for electric motor applications. This hybrid approach leverages multiple heat rejection pathways, resulting in improved thermal management, reduced power consumption, and a more compact design. At the core of the system, a thermal cradle incorporates a circular array of heat pipes that efficiently extract and dissipate the heat generated by the electric motor.

This new modeling methodology is particularly valuable for simulating thermal management systems in which liquid coolant-based subsystems interact significantly with one another, as commonly observed in advanced hybrid and electric vehicles. Enhancing the performance of liquid cooling systems is therefore crucial to improving the efficiency and thermal stability of EV motors, especially as power density continues to increase. In this context, innovative cooling topologies for electric machines are being developed, informed by advancements in components such as lubricating oils and motive seals used in electric vehicles. These innovations address several limitations observed in earlier designs, contributing to improved motor efficiency, reliability, and performance at higher energy densities.

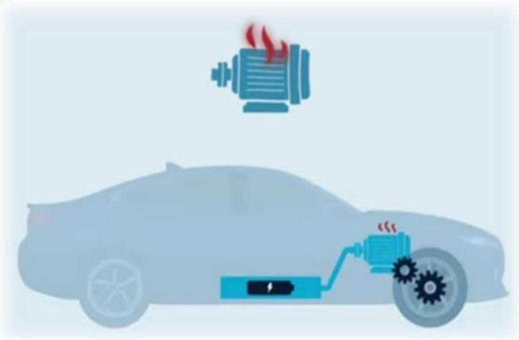


Fig 1.Heating of a motor in an Electric Vehicle

III. METHODOLOGY

The cooling system functions by continuously circulating coolant through narrow channels within the engine block. Driven by a fluid pump, the coolant flows through these passages, absorbing the heat generated by the engine during operation. Once heated, the coolant is directed to the radiator, where it releases the absorbed thermal energy. The radiator facilitates this heat dissipation by transferring it to the air that flows through the vehicle's front grille, effectively cooling the coolant before it recirculates back to the engine.

As the coolant passes through the radiator, it is cooled and prepared to return to the engine for another cycle of heat absorption. Positioned between the radiator and the engine is a critical component known as the thermostat, which acts as a regulator within the cooling system. When the coolant temperature falls below a specified threshold, the thermostat remains closed, allowing the coolant to bypass the radiator and recirculate directly back to the engine. This ensures the engine warms up efficiently. Once the coolant reaches the designated operating temperature, the thermostat opens, directing the flow through the radiator to dissipate heat before re-entering the engine, thereby maintaining optimal thermal conditions.

IV. MATLAB

MATLAB, short for **"Matrix Laboratory,"** is a high-level programming language and interactive environment designed primarily for numerical computation, data analysis, and visualization. It is widely used in engineering, science, and mathematics for solving complex mathematical problems.

MATLAB supports a wide range of data types, including numeric arrays, strings, structures, and cell arrays, making it versatile for various computational tasks. It includes a comprehensive library of built-in functions for performing mathematical operations, signal and image processing, statistics, optimization, and more. Additionally, MATLAB offers specialized toolboxes that extend its core capabilities, allowing users to tackle domain-specific problems in areas such as machine learning, control systems, and computational biology.

It provides robust tools for 2D and 3D plotting, enabling users to visualize data effectively. It supports a wide variety of plot types—such as line graphs, bar charts, surface plots, and contour maps—with extensive options for customization, making it ideal for technical presentations and publications.

MATLAB also allows for the development of standalone applications and graphical user interfaces (GUIs) using its built-in App Designer and GUI development environment. This feature enables researchers and engineers to create interactive tools and simulations based on their MATLAB code, facilitating user-friendly access to complex computational models.

Simulink: Simulink is a companion product to MATLAB that offers a graphical, block diagram-based environment for modeling, simulating, and analyzing multi-domain dynamic systems. It is particularly well-suited for applications involving control systems, signal processing, communication systems, and other complex engineering domains. By enabling users to design and simulate systems at the component level, Simulink facilitates rapid prototyping, system-level integration, and verification of dynamic behavior across electrical, mechanical, thermal, and hydraulic domains.

MATLAB offers robust integration capabilities with other programming languages and tools such as C/C++, Java, Python, and Microsoft Excel. It supports interoperability through multiple interfaces and file formats, enabling seamless data exchange and embedded system integration.

MATLAB is supported by a large global user community, which actively contributes to online forums, blogs, and educational content. MathWorks—the developer of MATLAB—provides comprehensive documentation, tutorials, and technical support, making it easier for users to learn and troubleshoot.

Due to its strong computational capabilities and user-friendly interface, MATLAB is extensively used in academia for both teaching and research. It spans a wide range of disciplines including engineering, mathematics, physics, biology, finance, and economics.

V. BLOCK DIAGRAM

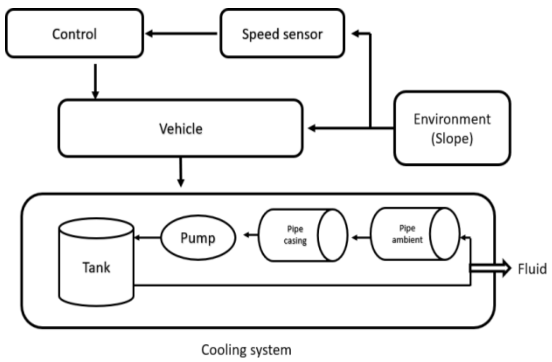


Fig 2. Block diagram of Electric Vehicle with cooling system

Overall, MATLAB's powerful combination of numerical computing, data visualization, system simulation, and application development tools makes it a highly versatile platform. Engineers, scientists, and researchers use MATLAB to efficiently model, analyze, and solve complex real-world problems across multiple domains.

Simscape: Simscape is a physical modeling tool within MATLAB and Simulink that enables engineers and scientists to model and simulate multi-domain physical systems. It employs a component-based approach, where systems are constructed as networks of interconnected blocks—each representing a physical element (e.g., resistor, mass, valve) or a mathematical relationship. Simscape facilitates modeling of various physical domains including electrical, mechanical, thermal, hydraulic, and fluid systems.

By enabling the integration of physical modeling with control logic and signal processing (through Simulink), Simscape provides a powerful environment for simulating and analyzing the behavior of complex dynamic systems. It is widely used across industries such as automotive, aerospace, energy, and robotics for tasks including system-level design, performance evaluation, and control system development.

Component-Based Modeling: Simscape uses a network of interconnected components to model physical elements and their interactions. Components represent basic physical elements like resistors, capacitors, springs, dampers, motors, valves, etc.

Multi domain Support: It supports modeling of various physical domains such as electrical, mechanical, hydraulic, thermal, and magnetic systems. This capability allows for the simulation of complex multi domain systems where interactions between different domains are critical.

1. Mathematical Foundation: Simscape leverages physical principles and equations to define component behavior, ensuring realistic simulations based on fundamental physics. This approach facilitates accurate representation of real-world systems.

2. Integration with Simulink: Simscape models are integrated seamlessly with Simulink, MATLAB's graphical simulation environment. This integration enables users to combine multi domain physical models with control systems, signal processing algorithms, and other Simulink functionalities.

3. Application Areas: It is widely used across industries for various applications including control system design, mechatronics, power systems, automotive systems, robotics, aerospace, and more. Engineers and researchers use Simscape for virtual prototyping, system-level design validation, and optimization.

4. Simulation and Analysis: Simulation capabilities in Simscape include time-domain simulation, frequency-domain

   analysis, parameter sweeps, sensitivity analysis, and optimization. These tools help users understand system behavior, evaluate design alternatives, optimize performance.

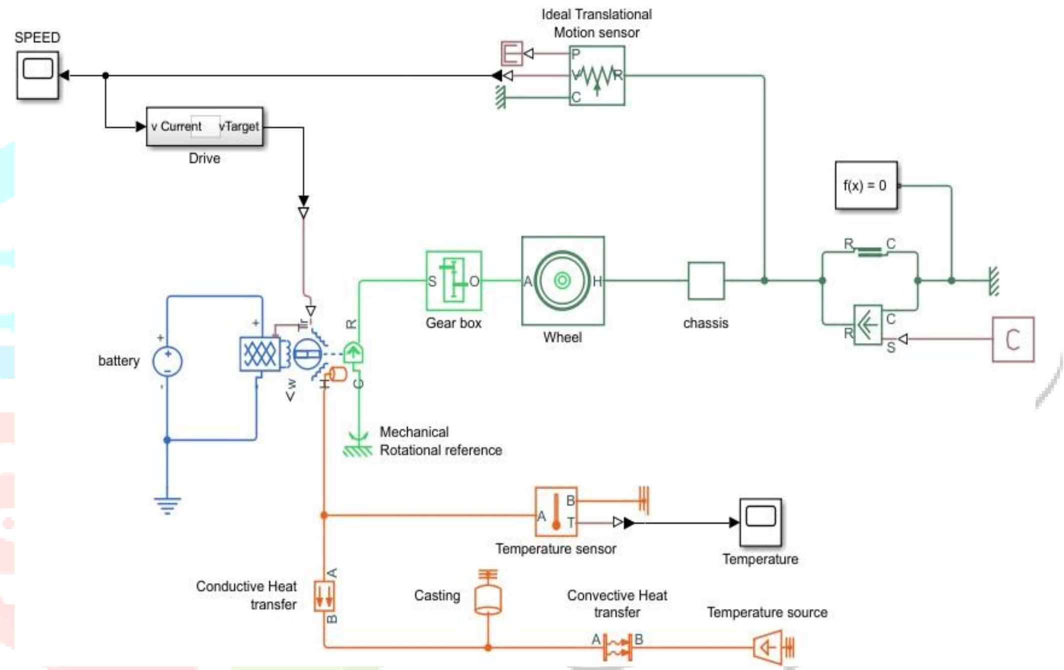
Overall, Simscape provides a robust platform for modeling complex physical systems, facilitating efficient simulation, analysis, and design across a wide range of engineering disciplines. Its integration with MATLAB and Simulink ecosystem enhances its versatility and usability in industry and academia alike.

VI. SIMSCAPE MODEL

6.1 Case 1: Electric Vehicle without Cooling system

A drive model has been added to control vehicle speed. The vehicle is traveling on a highway at cruising speed when it encounters a slower vehicle ahead. During the passing maneuver, the vehicle accelerates, temporarily stopping before returning to the original lane. While accelerating, the motor delivers 200 Newton-meters of torque. The passing time can be determined by examining the torque plot in the Simscape Results Explorer. This tool displays any Simscape variable over time. In this case, the torque remains constant for 14 seconds during the overtaking process—an extended duration to remain in oncoming traffic.

To monitor the motor temperature, a temperature sensor has been added. By clicking the Run button, the updated model can be simulated to observe how hot the motor becomes. The results show that the motor exceeds the desired temperature limit during acceleration and even while cruising, which indicates a thermal



management issue. This suggests the need to incorporate a

Fig 3. Simscape model of an Electric Vehicle without cooling system

cooling system into the model.

6.2 Case 2: Electric Vehicle with Cooling system

High-performance motors typically use liquid cooling to remove excess heat. This insight helps determine the necessary steps to maintain the motor within its rated temperature limits. Heat generated by the motor is transferred through the motor casing to the coolant, which then carries it to the radiator, where it is released into the surrounding environment.

Pipe blocks are used to model heat exchange between a moving fluid and the pipe wall. One pipe is configured to absorb heat from the motor, while another transfers heat to the environment. To complete the fluid loop, a tank and a mass flow source—acting as a pump—are added. Using the Fluid Properties block, the appropriate working fluid for the cooling system can be selected.

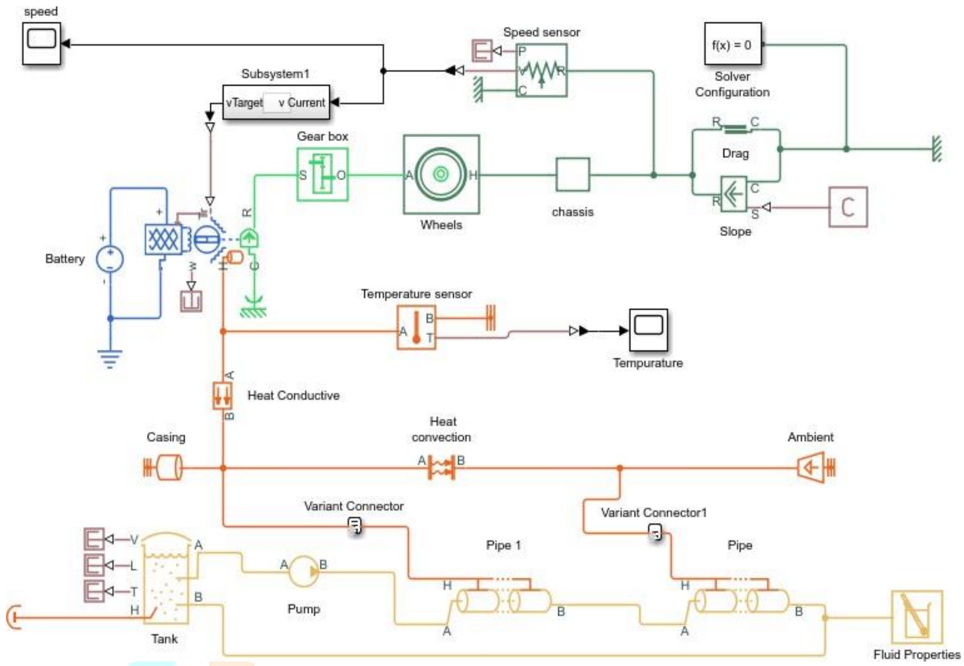


Fig 4. Simscape model of an Electric Vehicle with cooling system

Throughout the simulation, the motor temperature remains below 120°C, providing a substantial safety margin for high-performance operation. Within a short period, Simscape enables the sizing of both the motor and cooling systems using an electric vehicle model that includes the battery, motor, drive train, and wheels.

VII. RESULTS

The components in the model are connected in a manner that mirrors their configuration in the actual physical system. The lines connecting these components represent equations that define how they interact. Each individual component also includes its own set of equations describing its physical behaviour. Simscape automatically derives the system-level equations and solves them at each time step during the simulation.

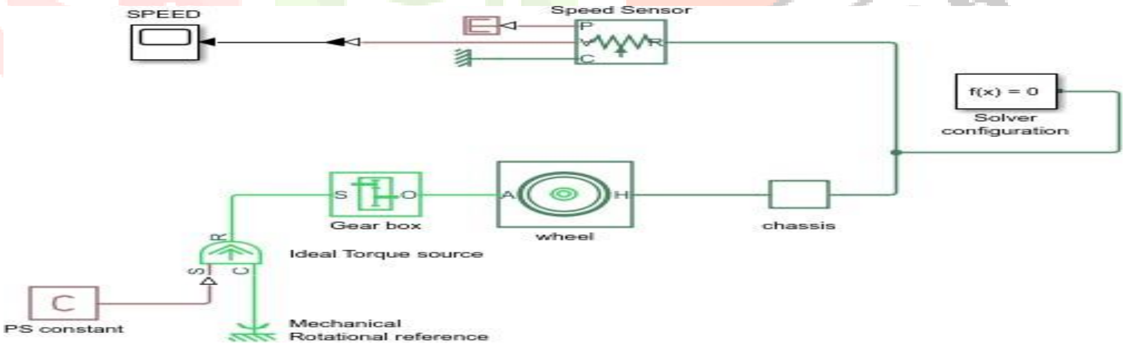


Fig 5. Simscape model of an Electric Vehicle

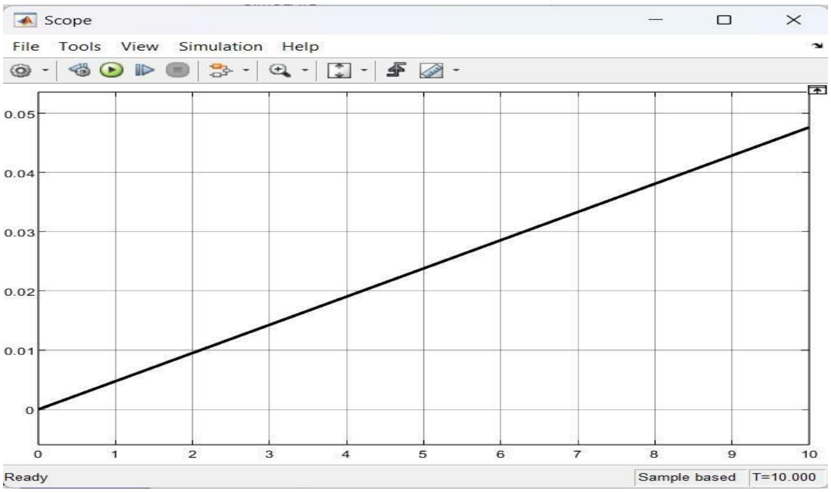


Fig 6. Speed of the vehicle

From the resulting graph, it can be observed that the vehicle continues to accelerate without limit, and the speedometer displays unrealistically high values. This indicates that certain physical effects are missing from the model. To achieve more accurate behavior, elements such as rolling resistance of the tires, aerodynamic drag, and road incline need to be included.

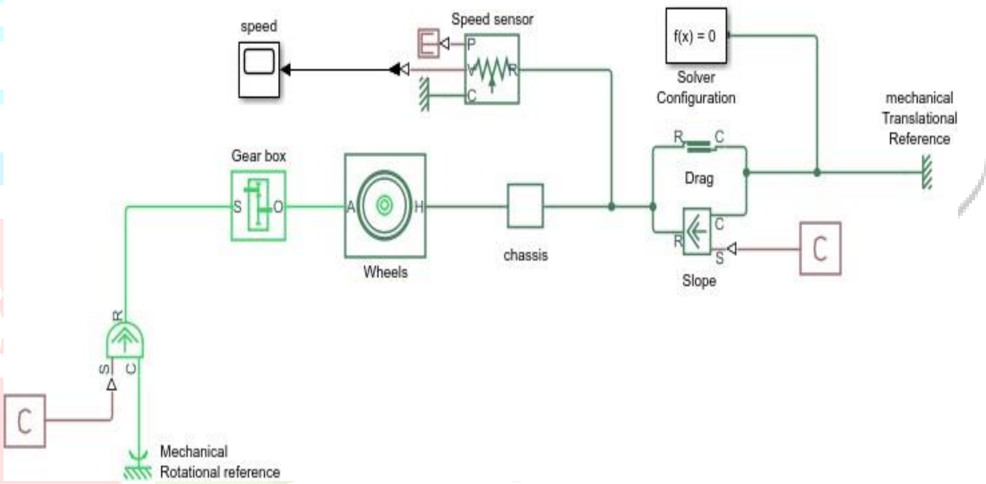


Fig.7. Electric vehicle with slope

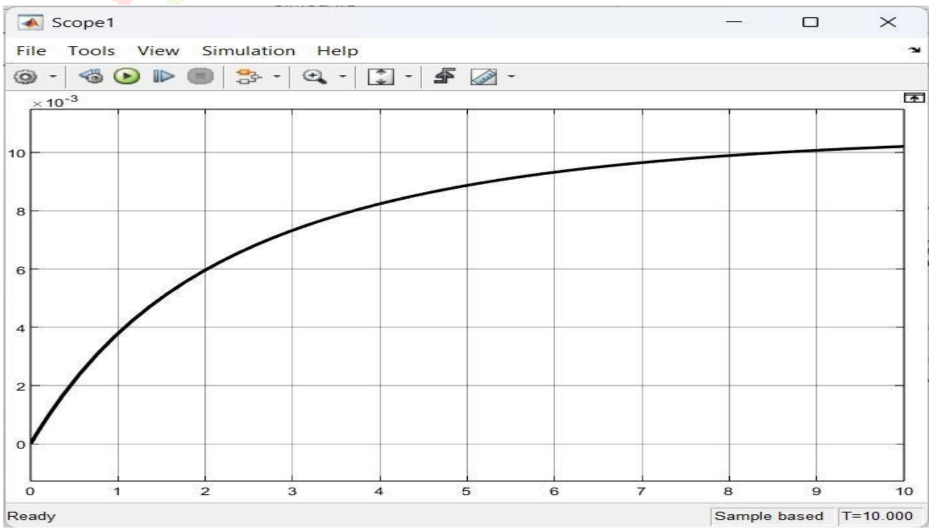


Fig 8. Speed of the vehicle after the slope created

Friction blocks have been added to capture rolling resistance and aerodynamic drag. Additionally, a force source is included to model the effect of gravity when the vehicle is driving uphill.

With these additions, the speed has been reduced but remains relatively high—an unrealistic scenario, as sustained full-throttle acceleration over several minutes is uncommon under normal driving conditions. Further refinement of the driving profile or control logic may be needed to better reflect real-world behaviour.

7.1 For Electric vehicle without cooling system the results are:

By increasing the torque, the passing time has been reduced to less than 4 seconds, which should satisfy even the most demanding performance requirements. A specific motor can be selected and its characteristics incorporated into the model. The chosen motor delivers a maximum torque of 800 Newton-meters and a peak power output of 500 kilowatts.

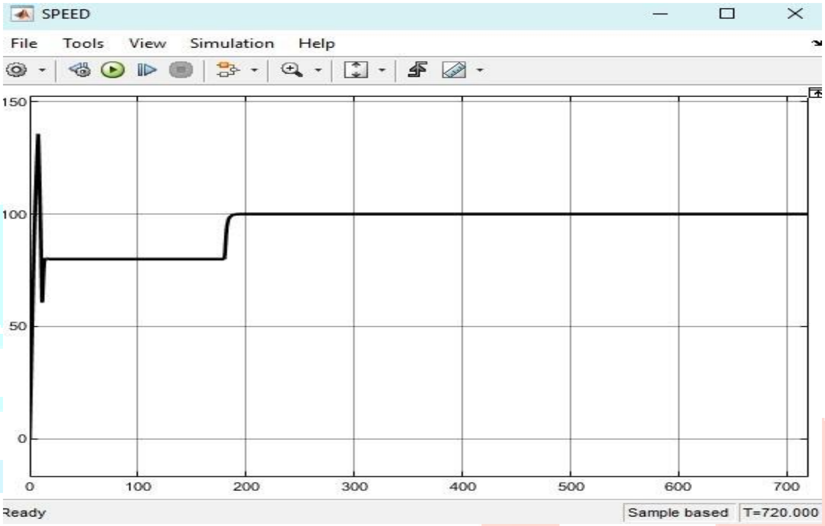


Fig.9. Speed of the vehicle

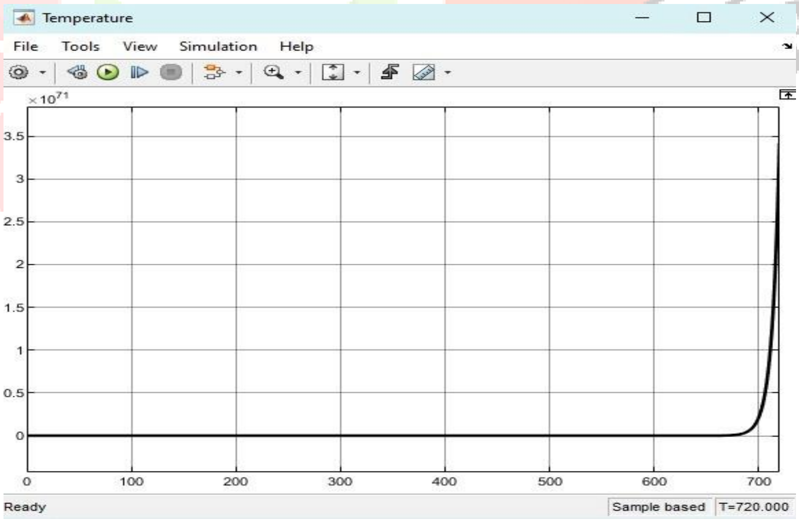


Fig.10.Temperature of the motor in without cooling system

Simscape provides multiple blocks to represent electric motors, each offering different levels of modelling detail, allowing for flexibility in system design and simulation fidelity.

Electric motors are not perfectly efficient some of the energy supplied by the battery is converted into heat rather than motion. To evaluate how this heat generation impacts motor temperature, the motor's thermal behaviour was modelled. This analysis helped determine the necessary steps to keep the motor within its rated temperature limits and assess how thermal effects can be incorporated into the overall system.

Table 1: Temperature values without cooling system

TIME (s)	SPEED (m/s)	TORQUE (N/m)	TEMPERATUR E (^0C)
100	25	100	120
200	40	800	250
400	28	100	140
600	28	100	160

7.2 For Electric vehicle with cooling system the results are:

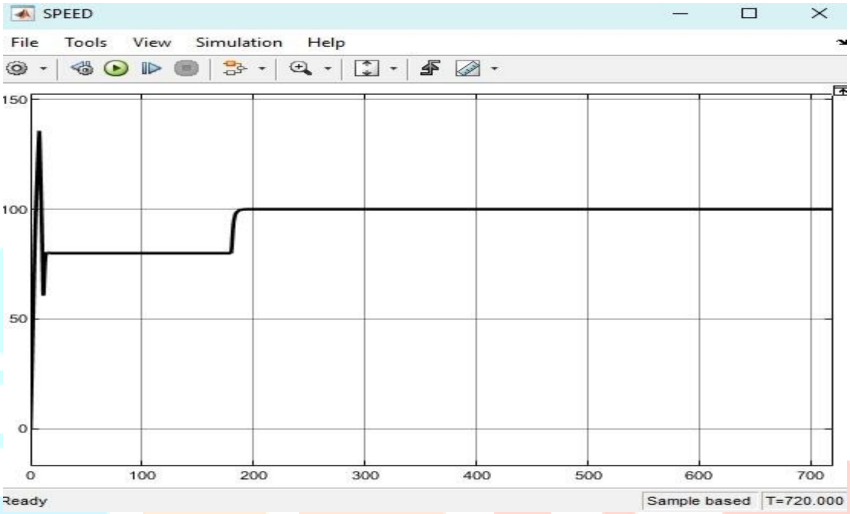


Fig.11. Speed of the vehicle

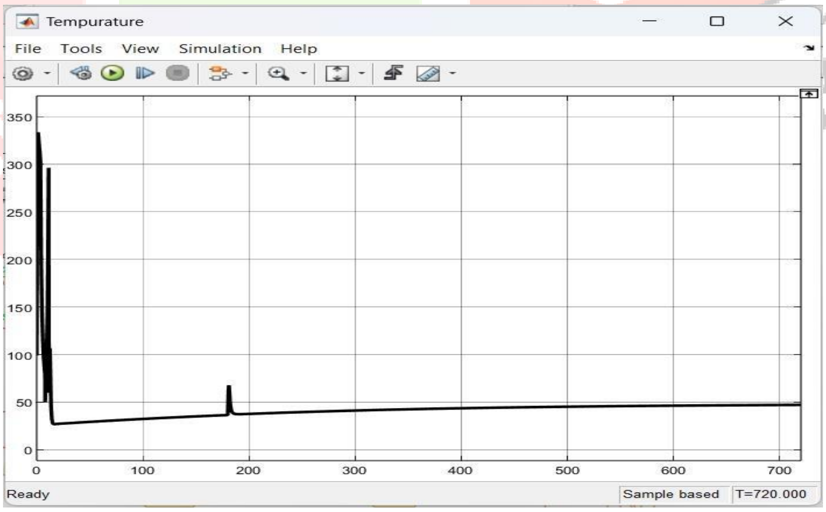


Fig.12.Temperature of the motor in with cooling system

A thermal port was added to the motor to model heat transfer to the environment, and a temperature sensor was included to monitor motor temperature during operation. By running the updated simulation, it was observed that the motor exceeds the desired temperature limit during both acceleration and cruising. This indicates the need to implement an effective cooling system to manage thermal performance and ensure reliability.

A thermal port was added to the motor to model heat transfer to the environment, and a temperature sensor was included to monitor motor temperature during operation. By running the updated simulation, it was observed that the motor exceeds the desired temperature limit during both acceleration and cruising. This indicates the need to implement an effective cooling system to manage thermal performance and ensure reliability.

Table 2: Temperature values with cooling system

TIME (s)	SPEED (m/s)	TORQUE (N/m)	TEMPERATURE (^0C)
100	25	100	70
200	40	800	90
400	28	100	50
600	28	100	45

The motor casing transfers heat to the coolant, which is then expelled to the environment through the radiator. Pipe blocks in the model are used to simulate heat exchange between the moving fluid and the surrounding walls. One pipe absorbs heat from the motor, while another transfers it to the environment. To complete the fluid loop, a tank and a mass flow source—acting as a pump—are included. The Fluid Properties block allows for the selection of the appropriate coolant for the system.

Throughout the simulation, the coolant temperature remains below 120°C, providing a significant safety margin even under high-performance operating conditions. Within minutes, Simscape enabled the accurate sizing of the motor and cooling system in an electric vehicle model that includes the battery, motor, drive train, and wheels.

VIII. CONCLUSION

Using MATLAB Simscape to model the electric vehicle motor cooling system provided valuable insights into the motor's thermal performance during operation. The simulation demonstrated how motor temperature fluctuates under varying load conditions and how different cooling methods influence both performance and thermal regulation.

The results confirmed that liquid cooling is highly effective in maintaining optimal motor temperature, particularly during high-load scenarios. This method enhances performance, ensures operational safety, and extends motor lifespan, making it a robust and reliable solution for thermal management in electric vehicles.

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