A Study on Model-Based Thermal Management Systems Architecture Modeling and Energy Efficiency Prediction of Fuel Cell Electric Vehicles

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Abstract

The purpose of this study is to predict the energy efficiency of Fuel Cell Electric Vehicles (FCEVs) based on the configuration of the Thermal Management System (TMS). The energy efficiency of an FCEV is closely tied to the effective thermal management of the electric powertrain. Therefore, this paper investigates TMS modeling for FCEVs and multi-physics modeling of FCEVs. The main modules of the target multi-physics FCEV model include the vehicle dynamics model, thermal management system, electric powertrain and controller. The main research focus is the water-cooled TMS architecture. The main thermal management components (heat-generating components) include the fuel cell, battery, motor and BOP (Balance of Plant). The model was developed using Modelica and used to predict the energy efficiency under various driving conditions (extremely cold, moderate and extreme heat) and driving conditions.

Keywords: Vehicle System Engineering, Thermal Management System, Fuel Cell Electric Vehicle

1 Introduction

The transition towards eco-friendly and sustainable transportation has accelerated the development of alternative powertrain systems, such as Fuel Cell Electric Vehicles (FCEVs). FCEVs, which use hydrogen fuel cells as their primary energy source, offer the advantages of high efficiency and zero-emission operation. However, they present critical challenges in terms of thermal management. Efficient thermal management is essential to maintain the optimal operating of fuel cells and other key components. This ensures passenger comfort, extends vehicle life, and optimizes overall energy consumption.

Thermal management in FCEVs is highly complex, as it must account for varying power demands, dynamic environmental conditions, and the unique operational characteristics of fuel cells, which generate both heat and water as byproducts. A robust TMS is necessary to effectively distribute and dissipate heat, minimizing energy losses and optimizing performance under diverse driving conditions. To optimize the TMS architecture of FCEVs, it is crucial to develop multi-physics models integrating thermal, electrical, and dynamic systems.

This paper proposes a Modelica based modeling approach of TMS architecture and the prediction of FCEV performance under varying conditions. Model-based approaches provide a structured and predictive method for designing and analyzing the TMS architecture of FCEVs, especially in the early stages of design. Modelica, a non-proprietary, object-oriented, equation-based modeling language, is particularly suitable for this purpose. Modelica supports the integration of thermal, electrical, and fluid systems into unified multi-domain models, enabling the analysis of complex interactions within FCEV TMS and the prediction of energy efficiency using a single simulation framework.

In this study, we aim to develop a model-based approach using Modelica to model the TMS architecture of FCEVs and accurately predict energy efficiency under various operating conditions. The objective of this research is to provide a systematic method for TMS design and control that enhances the energy efficiency and reliability of FCEVs.

2 Methodology

In this paper, vehicle dynamics, electric powertrain, and TMS models are developed to predict the performance changes of FCEVs by TMS architecture. The vehicle dynamics model was built using the Vehicle Dynamics Library from *Modelon AB*, while the electric powertrain model was based on *Modelon AB*'s Electrification Library. The TMS was modeled using the Thermal Systems Library from *TLK-Thermo GmbH*. The integrated model was constructed using Dymola from *Dassault Systèmes*.

2.1 Vehicle Model

The vehicle model is organized in a hierarchical structure, and includes detailed sub-systems such as the Chassis System, Thermal Management System, Powertrain System, and Brake System.

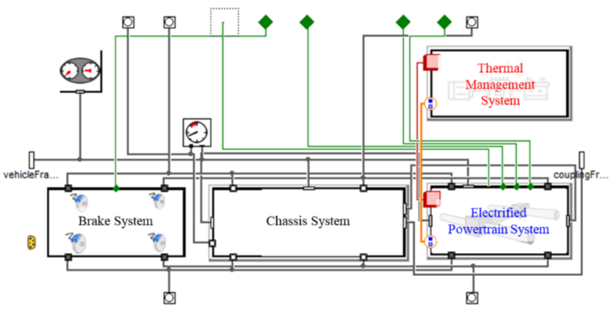

Figure 1. Vehicle Model

Each sub-system exchanges Dynamics, Electrical, and Thermal signals. The Powertrain System transfers the heat generated during operation to the TMS, and the powertrain model transmits both the power and movement produced by the Fuel Cell, battery, and motor to the Chassis System.

2.2 Chassis Model

The chassis model consists of front and rear suspension, frame, wheel, and body models. The suspension model transmits vibrations from the wheel model to the body. It is constructed using a multi-body dynamics approach. However, since this model is designed for energy efficiency prediction, the bushing models are simplified and replaced with joint models.

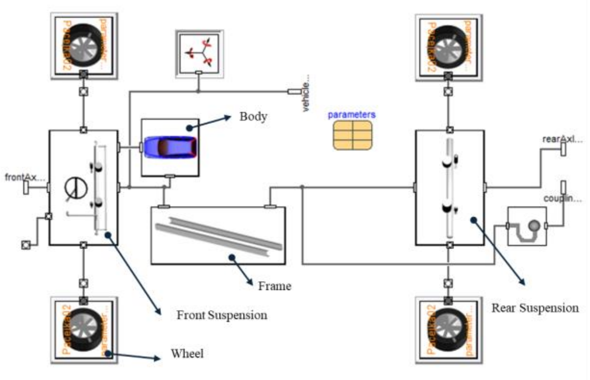

Figure 2. Chassis Model

2.3 Electrified Powertrain

The main components of the electrified powertrain model are the battery model, hydrogen fuel cell, and motor.

The battery model is parameterized with cell capacity, open-circuit voltage curves, internal resistance values, and cell configurations. It generates power while producing heat during operation.

The hydrogen fuel cell model is built based on the battery model. It calculates hydrogen consumption based on power demand and shares a similar structure with the battery model. By connecting a load model that simulates the power consumption of the Balance of Plant (BOP), the total output (gross output) and net output can be calculated. Like the battery model, the fuel cell model generates heat during power production.

The motor model incorporates torque maps and efficiency maps as parameters and includes a maximum torque limit. It generates driving torque according to the vehicle's speed requirements by receiving power from the battery model and hydrogen fuel cell model. The generated driving torque is transmitted through the driveline to control the vehicle's speed. Heat is produced due to losses occurring during torque generation.

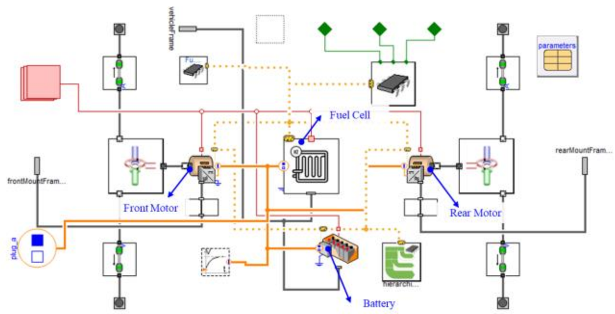

Figure 3. Electrified Powertrain Model

2.4 Thermal Management System

In this vehicle model, the primary heat-generating components are the hydrogen fuel cell, battery, and motor. Due to the different optimal operating temperatures of each component, the cooling cycles are configured independently. In addition to the 4 major heat-generating components mentioned above, other components requiring thermal management include the Low Voltage DC-DC Converter (LDC) for low-voltage equipment in the vehicle, the Balance of Plant (BOP) responsible for managing fuel, moisture, air, and power distribution, and the Fuel Cell DC-DC Converter (FDC), which ensures stable delivery of electricity generated by the hydrogen fuel cell stack to the high-voltage battery for charging or to the inverter.

Table 1. List of heat generating components by cycle

Cycle Name	Heat Components Name
Battery Cycle	Battery
PE Cycle	Front PE

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	Rear PE
	BOP
	LDC
	FDC
FC Stack Cycle	Fuel Cell

Each cooling cycle operates independently, forming a total of three separate cycles. There is no cross-flow or mixing between the coolant of these cycles. Different cooling liquids should be used depending on operating conditions (voltage and current), but this model is simplified by using a single cooling liquid for all cycles.

Table 2. Coolant by cooling cycle

Cycle Name	Liquids
Battery Cycle	Ethylene Glycol 50%
PE Cycle	
FC Stack Cycle	

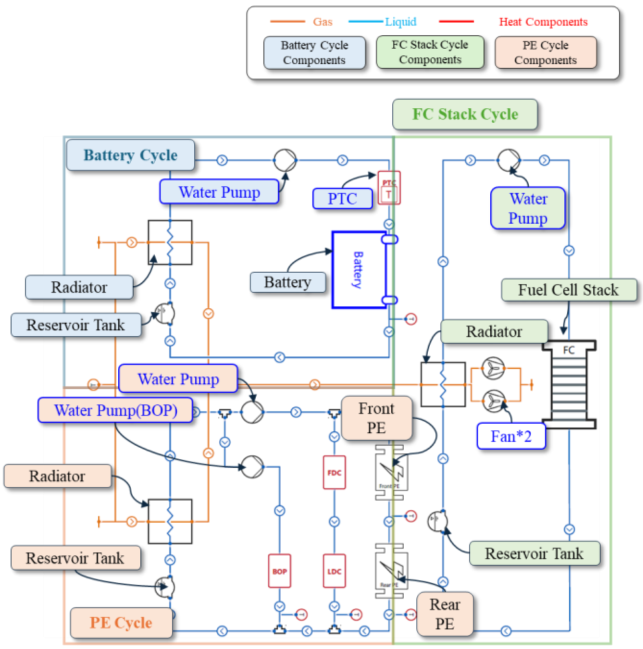


Figure 4. TMS Architecture

The actuators for each cycle are as follows, and they consume power during operation. Consequently, the consumed power is accounted as a load, which reduces the battery's available power.

Table 3. List of Actuators by Cooling Cycle

Cycle Name	Actuator
Battery Cycle	Water Pump
	PTC
PE Cycle	Water Pump
	Water Pump(BOP)
FC Stack Cycle	Water Pump
Common	Fan

2.5 Controller

To meet the target temperature of each cycle, the actuators within each cycle must be operated based on the state variables of the cycle and its components. Accordingly, a controller model is required, where the controller adjusts the actuators according to the temperatures of the components within the cycle. The actuators in each cycle control the water pump based on the outlet temperatures of individual components and ambient temperature. In the battery cycle, the PTC (Positive Temperature Coefficient heater) is additionally controlled to heat the battery as needed. The fan adjusts its volumetric flow rate using the outlet temperatures of the battery, fuel cell stack, PE, LDC, BOP, and the ambient temperature.

2.6 Scenario

The Chassis, Electrified Powertrain, Thermal Management System, and Controller configured above are integrated into the Vehicle Model. In order to predict the power consumption of a vehicle model, the vehicle model is driven according to the Drive Cycle, and the Drive Cycle utilized is the Worldwide harmonized Light vehicles Test Cycle (WLTC). The WLTC (Worldwide harmonized Light vehicles Test Cycle) is a globally standardized driving cycle used to measure the fuel consumption, CO_2 emissions, and pollutant emissions of passenger cars and light-duty vehicles. It was developed by the UNECE (United Nations Economic Commission for Europe) as part of the WLTP (Worldwide harmonized Light vehicles Test Procedure) framework. In this study, to reflect the limitations of the electrified powertrain in the vehicle model, the drive cycle was modified with an upper speed limit of 120 kph, and performance predictions were conducted based on the adjusted cycle. In this scenario, the WLTC was repeated for 2 cycles.

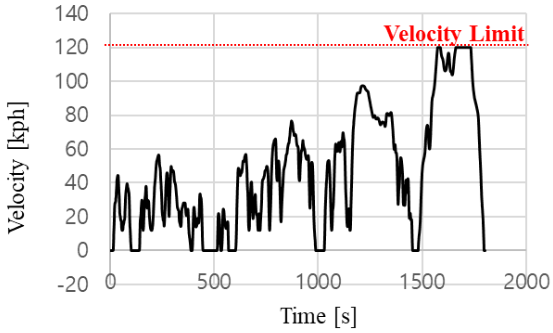
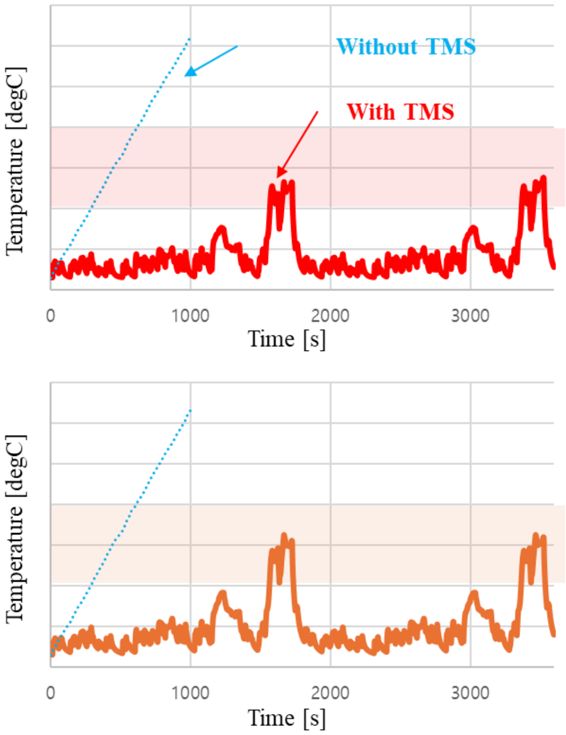


Figure 5. WLTC speed profile reflecting vehicle driving limit performance

3 Result

- Components Temperature(Extreme Hot)

In the extreme hot scenario, it was observed that the temperature of the Front and Rear PEs requires control for only a short duration, yet it remains within the target temperature range. The FC stack also showed a short control duration, successfully converging within the target temperature range. For the battery, due to the minimal operational time governed by the control conditions (drive control), heat generation was negligible, resulting in insignificant temperature changes.



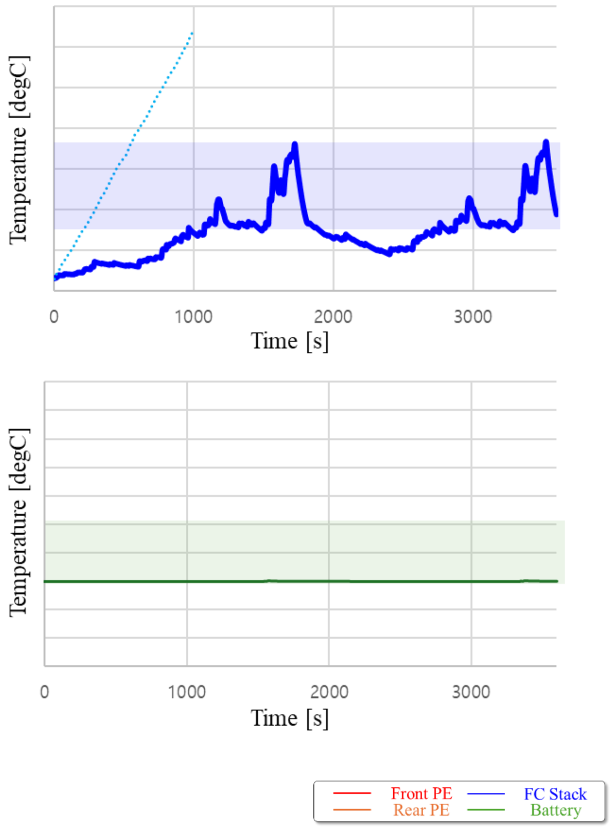
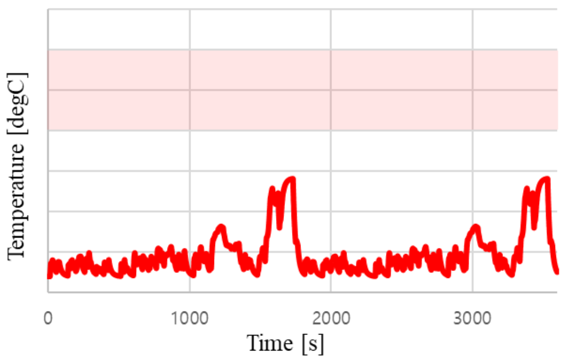


Figure 6. Components Temperature in Extreme Hot

- Components Temperature(Moderate)

Under moderate conditions, it was confirmed that the temperature levels of the components are lower compared to extreme heat conditions. Rear PE is located further back than the Front PE, resulting in slightly higher temperatures, but it still did not reach the optimal temperature. FC Stack reached the optimal temperature range during certain high-speed sections, indicating that its temperature is being effectively controlled by the controller. Meanwhile, the battery exhibited very low heat generation due to driving conditions, similar to extreme heat conditions.



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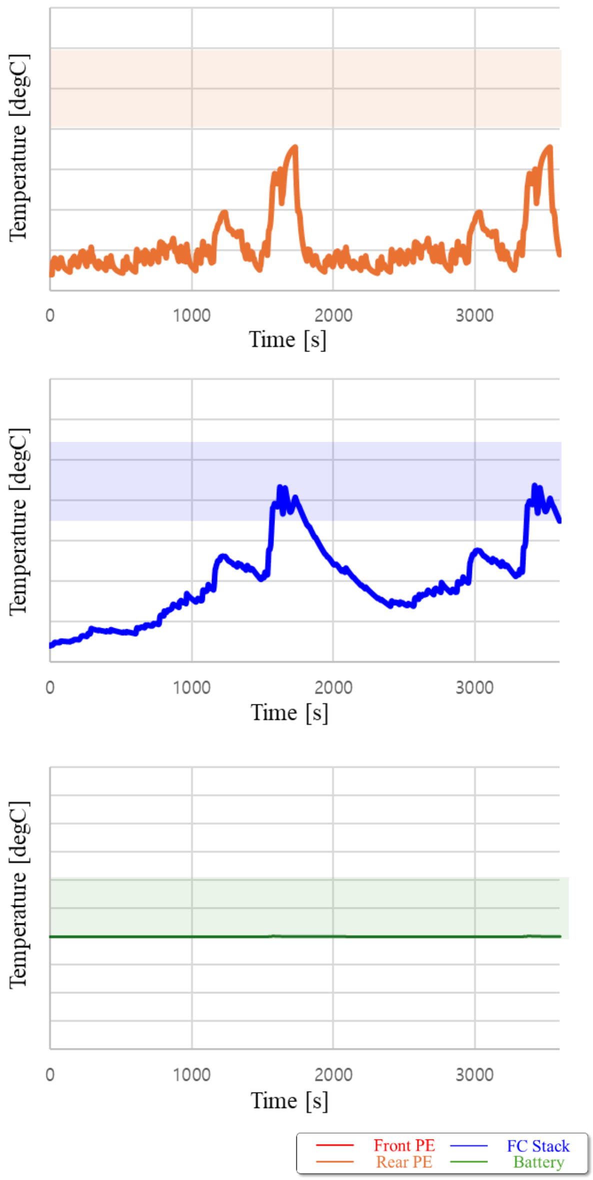

Figure 7. Components Temperature in Moderate

- Components Temperature(Extream Cold)

Under extreme cold conditions, it was observed that the Front PE, Rear PE, and FC Stack could not reach their target temperatures solely through self-heating. Particularly for the FC Stack, failing to achieve its target temperature can lead to overall efficiency degradation, reduced lifespan, and decreased power output. Therefore, it is necessary to consider the integration of forced heating components, such as a COD heater and air heater, within the system architecture.

The battery, equipped with a PTC heater, raises the cooling water temperature within the battery cycle when the ambient temperature is low. After reaching the target temperature, temperature control is carried out to maintain the optimal temperature range. This demonstrates the effective temperature management within the battery cycle under extreme cold conditions.

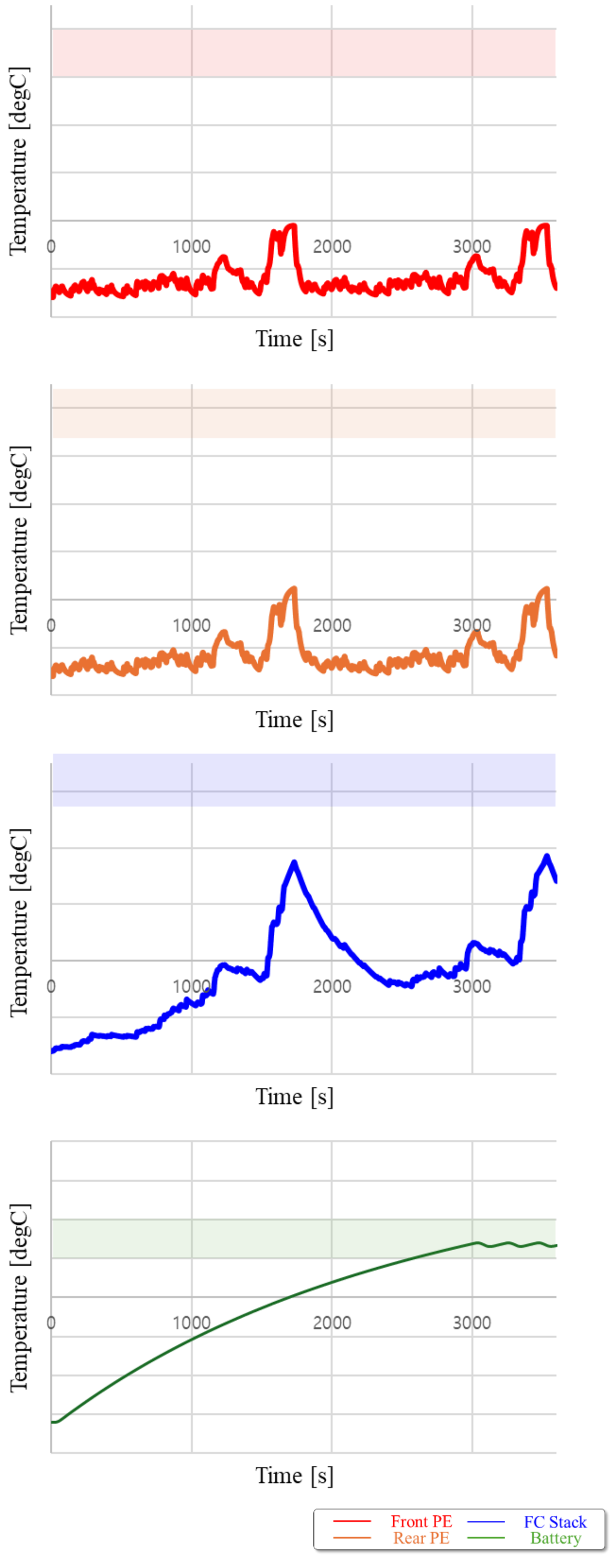

Figure 8. Components Temperature in Extreme Cold

- Hydrogen consumption

The model developed in this study does not include parameters that can reflect individual component performance changes based on their temperatures. Therefore, the changes in vehicle system performance due to component temperatures are predicted through variations in hydrogen consumption.

Under extreme hot conditions, the presence of a TMS leads to increased hydrogen consumption due to the operation of fans and water pumps to maintain component temperatures within the optimal range. In this study, as efficiency data based on component temperatures was not considered, it was observed that hydrogen consumption is higher with the application of TMS compared to when TMS is not applied.

Even under moderate conditions, the presence of a TMS results in increased hydrogen consumption, as fans and water pumps are operated to control component temperatures within the optimal range. However, compared to extreme heat conditions, the duration of temperature control to maintain the target component temperatures is shorter, leading to lower hydrogen consumption.

Under extreme cold conditions, hydrogen consumption increased significantly compared to extreme heat and moderate conditions. This is attributed to the substantial rise in high-voltage power usage caused by the operation of the PTC heater.

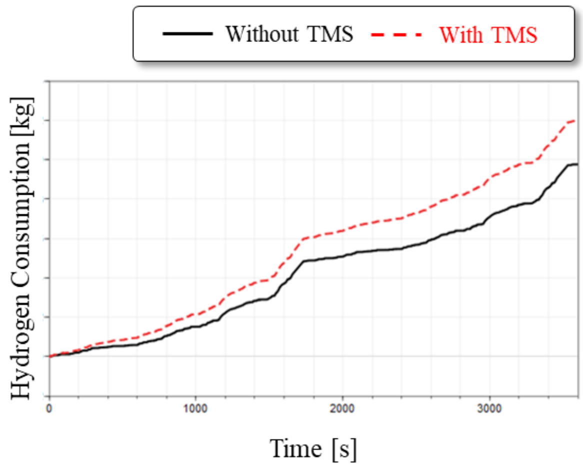

Figure 9. Hydrogen consumption by With/Without TMS in Extreme cold conditions

Table 4. Hydrogen consumption according to ambient conditions and TMS

Ambient Condition	TMS	Hydrogen Consumption
Extreme Hot	X	+
	O	+++
Moderate	X	+
	O	++
	X	+
Extreme Cold	O	++++

4 Conclusion

This study developed a model-based approach for modeling the TMS architecture and predicting the energy efficiency of FCEVs using Modelica. By integrating vehicle dynamics, thermal management, and electric powertrain systems, this model highlights the importance of thermal management in optimizing system performance under various environmental conditions. The study results indicate that TMS operations, influenced by external conditions, activate components such as fans, water pumps, and PTC heaters, leading to variations in hydrogen consumption. Under extreme heat conditions, TMS increases hydrogen consumption as it controls component temperatures, while in moderate conditions, the impact is relatively smaller due to shorter control durations. In contrast, under extreme cold conditions, hydrogen consumption increases significantly as the PTC heater operates to achieve target temperatures, emphasizing the necessity of effective thermal management in extreme conditions.

However, the current model does not include performance change data for individual components based on temperature variations, preventing direct assessment of TMS-related energy efficiency changes. This study underscores the importance of advanced TMS architectures for maintaining optimal component temperatures and improving energy efficiency. Future research should focus on parameterizing performance changes in individual components caused by temperature variations and exploring alternative thermal management strategies that can reduce energy losses while maintaining system stability.

Acknowledgements

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