

Performance Evaluation of 45kW Low Temperature Proton Exchange Membrane Fuel Cell System Using Simulation Techniques

Karthikeyan Subramanian^{1,*}, Parthiban.Siva Gurunathan², Venkatesh Kumar .Velmurugan³

Abstract

The Low-Temperature Proton Exchange Membrane Fuel Cell (LT-PEMFC) has gained prominence as a promising solution for clean and efficient energy generation, particularly in the automotive industry, where stringent emission norms and sustainability goals are driving innovation. LT-PEMFC systems offer several inherent advantages, including high energy conversion efficiency, low operational temperature, rapid start-up capability, and compatibility with hydrogen as a renewable fuel source. These characteristics make them attractive for commercial vehicle applications, where reliability and performance are critical. Despite these benefits, large-scale commercialization of LT-PEMFC technology remains challenging due to the complexity of system integration and cost considerations. The fuel cell stack must operate in conjunction with multiple Balance of Plant (BoP) components, such as air compressors, humidifiers, heat exchangers, and cooling circuits, which are essential for maintaining optimal operating conditions. Additionally, the selection of catalytic materials and membrane properties significantly influences electrochemical performance and durability. The interdependence of these subsystems often results in increased design complexity, higher manufacturing costs, and reliability concerns, limiting competitiveness against conventional internal combustion engines. To address these challenges, dynamic performance evaluation under realistic operating conditions is crucial. This study focuses on modeling and simulation of an LT-PEMFC system integrated with its BoP components using AVL CRUISE™ M, a widely adopted 1D simulation platform for automotive applications. The primary objective is to analyze system behavior and performance parameters to achieve a target power output of 45 kW, suitable for commercial vehicles. The simulation incorporates real-world duty cycles to evaluate transient responses, thermal management strategies, and hydrogen consumption patterns. The findings of this work aim to provide insights into improving system efficiency, reducing development time, and enhancing cost-effectiveness through virtual prototyping. Furthermore, the study highlights the role of advanced modeling techniques in accelerating LT-PEMFC adoption for sustainable transportation solutions, contributing to global efforts toward decarbonization and clean energy deployment.

Keywords: Fuel cell; PEM; Bop; Simulation; Stack area

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INTRODUCTION

Currently, nonrenewable fossil-based fuels remain the primary energy source for most mobility applications, significantly contributing to CO₂ emissions [1]. As a result, exploring the use of renewable fuels such as hydrogen is essential for transitioning automobiles toward green energy through the research and development of innovative strategies [1, 2]. In support of this green energy shift, efforts are now underway to develop high-

power fuel cell systems for commercial vehicles. Furthermore, a fuel cell is a power generation system that produces electricity and water through the electrochemical reaction between hydrogen and oxygen (from air). The core component of a fuel cell system is the central stack, which contains a series of reactive membranes [3, 4]. Among the various membrane types, the Polymer Electrolyte Membrane Fuel Cell (PEMFC) is particularly well-suited for automotive applications due to its relatively low operating temperature (below 100 °C) and high efficiency (Figure 1).

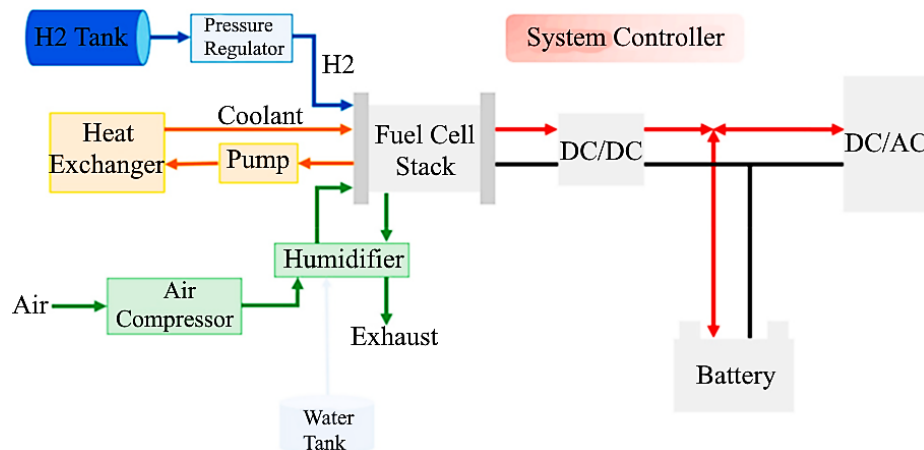


Figure 1. Schematic layout of PEM fuel cell.

Illustrates the schematic layout of PEM fuel cell. The PEM fuel cell system comprises two electrodes the anode (AN) and cathode (CL) along with a catalyst layer, gas diffusion layer (GDL), and a proton exchange membrane (PEM). Despite significant advancements in performance, reliability, and stability over recent decades, the cost of PEMFCs remains considerably high. Additionally, due to the system's multi-domain nature, modeling it accurately poses substantial challenges [5, 6].

Key Issues in Modeling PEM Fuel Cell Systems for Simulation Include

- Balancing model complexity and computational time with the need to realistically represent the application.
- Establishing a robust methodology for verifying model accuracy.
- Availability of both intrusive and non-intrusive measurement techniques.
- Limited access to performance data from existing fuel cell systems.

These challenges make model validation one of the most critical and demanding aspects [7]. However, selecting an appropriate trade-off in model complexity can enable effective simulation of key performance characteristics.

When modeling a fuel cell system using this AVL CRUISE™ M software, it is crucial to define not only the fuel cell stack but also supporting subsystems such as the radiator, hydrogen supply system, and balance of plant (BoP). Additionally, specifying dynamic operating states and environmental conditions is vital for accurate simulation. The validation environment includes energy-related parameters such as hydrogen concentration, ambient temperature, and pressure.

This study conducts a simulation of fuel cell stack performance using actual test data from an existing stack configuration. To further enhance performance, the stack area is increased, and the resulting impact is analyzed. Key performance metrics such as system power, stack power, efficiency, hydrogen consumption, air pressure ratio, compressor speed, and radiator cooling temperature are compared across configurations. Annexure 1 a. shows fuel cell components in AVL CRUISE™ M used for this simulation study. Based on the simulation results, the effort required to optimize these parameters in a vehicle is significantly reduced.

Furthermore, numerous simulation research efforts have been directed towards improving the fuel cell polarization curve by optimizing the stack area [8–10]. These investigations typically focus on analyzing parameters such as current density and temperature distribution across the stack, as predicted by advanced fuel cell modeling techniques [10–14]. However, in this study, AVL CRUISE™ M software is employed to simulate the performance of fuel cell systems based on truck operating duty cycle. This comprehensive simulation tool integrates all key components associated with fuel cells, making it an essential resource for fuel cell system development in the automotive sector. Its use significantly reduces both development time and cost [15–20].

AVL CRUISE™ M Simulation

AVL CRUISE™ M is a dynamic simulation platform equipped with multifunctional capabilities and a comprehensive library of pre-configured templates for various automotive applications. It serves as a powerful tool for conceptualizing and designing systems that closely replicate real-world operating conditions. In addition to system design, the software is instrumental in identifying design flaws and diagnosing root causes of performance issues. Fundamentally, AVL CRUISE™ M is a multi-physics simulation environment that enables model and system development using a wide range of specialized libraries, including the following Thermal parameters for various heat transfer

- Flow of any fluid, gas, liquid, or mixture
- Electric and electromagnetic curves of circuits and electromechanical devices
- Chemical kinetics
- Signal processing and control

With its robust productivity tools and multi-physics modeling capabilities, AVL CRUISE™ M is well-suited for the optimization, analysis, and simulation of fuel cells and their associated subsystems. The software can simulate the performance of critical components such as the cooling system, gas supply systems for both the cathode and anode, the humidification unit, and the overall hydrogen consumption of the fuel cell. Beyond fuel cell system design, AVL CRUISE™ M also facilitates integration with interfacing systems for heat, water, air, and fuel management. As such, it is recognized as one of the most effective tools for simulating and optimizing fuel cell performance. Overall, it supports simulation under various dynamic states and transient driving cycles, enabling comprehensive performance evaluation [20].

Fuel Cell System Modeling and Simulation

The modeling process starts with defining the overall system architecture. This involves selecting the appropriate fuel cell system configuration and identifying key subsystems, including the fuel cell stack, Balance of Plant (BoP) components, and power electronics. Using the software's component library, essential elements such as the number of fuel cell stack to be added to the model and configured with parameters like number of stacks, geometry details to be provided. Table 1. Design parameters used for fuel cell system.

Table 1. AVL CRUISE™ M simulation capability.

1	Stack power vs Time
2	System power vs Time
3	Hydrogen fuel consumption vs Time
4	Stack & System power efficiency
5	Stack voltage/ Current
6	Stack cooling temperature
7	Radiator cooling temperature
8	Compressor before temperature
9	Intercooler after temperature
10	Relative humidity
11	Air compressor speed
12	Air compressor pressure ratio

BoP components typically include air compressors, humidifiers, heat exchangers, and cooling systems. For the powertrain, components such as DC/DC converters, inverters, electric motors, and energy storage systems are incorporated. Each element is parameterized based on experimental data. For the fuel cell stack, this include electrochemical characteristics such as activation, ohmic, and concentration losses, along with temperature and pressure dependencies. Efficiency maps are used for BoP components. Once the appropriate mechanical and electrical components are sized, the next step involves designing and modeling the flow paths for coolant, gas, air, and hydrogen. These flow configurations are illustrated in Annexure 1b. Further, control logic is also implemented using the function network within CRUISE™ M. This includes managing air and hydrogen flow, thermal regulation strategies, and power distribution between the fuel cell and auxiliary systems. To simulate real-world performance, standard, or custom truck driving cycles are imported. These cycles define the dynamic load conditions the system will encounter, enabling accurate performance evaluation.

The key parameters influencing fuel cell performance include current, voltage, power output, efficiency, and various temperature levels [21]. Based on the simulation results, these performance metrics are analyzed and compared to determine the optimal stack area for vehicle applications. Additionally, Figure 2 outlines the simulation capabilities available within the AVL CRUISE™ M software.

RESEARCH METHODOLOGY

The research methodology adopted for simulating fuel cell performance is illustrated in Figure 3. The overall process is structured into distinct phases: an initial literature review, followed by the development of the simulation model, and an experimental study to generate input data. The final phase involves validating the model under defined operating and environmental conditions.

RESULTS AND DISCUSSION

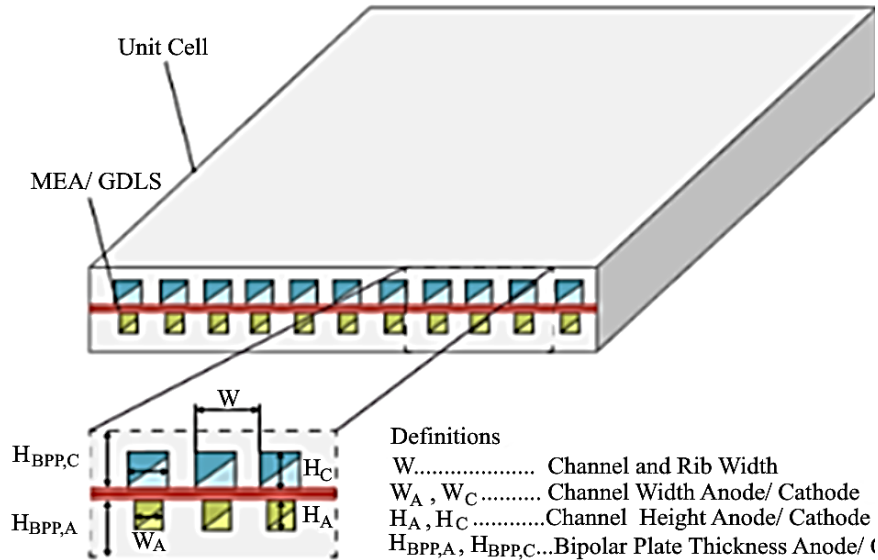
Figure 4 shows the fuel cell stack current vs time. The fuel cell stack current responded dynamically to fluctuating power demands, effectively simulating real-world load conditions. As depicted, the current surged to approximately 140 A during periods of high demand, particularly when the stack reached its maximum power output of 45 kW. This dynamic response highlights the stack's capability to swiftly adapt to load variations, maintain operational stability, and meet transient power requirements without compromising performance.

Figure 5 displays the fuel cell stack's power output over time. To simulate realistic operating conditions, the stack was subjected to dynamically varying load profiles that represent both transient and steady-state scenarios commonly encountered in real-world applications. Under these conditions, the stack reached a peak power output of 45 kW. During high-demand periods, the system consistently delivered power with minimal voltage ripple and current oscillation, highlighting its strong load-following capability and the effectiveness of the power conditioning system.

Figure 6 illustrates the fuel cell stack voltage output of the fuel cell stack over time. To simulate real-world operating conditions, the stack was subjected to dynamically varying load profiles that included both transient surges and steady-state demands. Under these conditions, the system successfully delivered a peak power output of 45 kW at approximately 300 V. The stack voltage varied in response to load changes, decreasing from around 360 V under low-load conditions to approximately 300 V at peak power. Despite rapid load fluctuations, the voltage remained within operational limits, demonstrating the system's robust dynamic response and effective voltage regulation.

The Figure 7 illustrates the current density profile over time. The performance of the Proton Exchange Membrane (PEM) fuel cell was evaluated under dynamically varying load conditions to assess its current density behavior. Current density, defined as the current per unit active area of the fuel cell, is a critical parameter influencing both efficiency and durability. During low-load conditions, the current density remained relatively low, reflecting minimal power demand. As the load increased, the current

density rose proportionally, reaching a peak of approximately 0.6 A/cm² at a maximum power output of 45 kW. This peak was achieved with an active cell area of 230 cm², indicating the system's ability to handle high transient loads effectively.



▼ Structure

Number of Cells in a Stack	<input type="text" value="370"/>
Active Cell Area:	<input type="text" value="229.6"/> cm ²
Bipolar Plate Design:	<input type="text" value="Machined"/>
Channel Length:	<input type="text" value="280"/> mm
Channel and Rib Width (W):	<input type="text" value="2.2"/> mm

▼ Anode Geometry

Channel Width:	<input type="text" value="1"/> mm
Channel Height:	<input type="text" value="1"/> mm
Bipolar Plate Thickness:	<input type="text" value="2"/> mm
Scaling Factor Gas Volume:	<input type="text" value="1"/> [-]

▼ Cathode Geometry

Channel Width:	<input type="text" value="1"/> mm
Channel Height:	<input type="text" value="1"/> mm
Bipolar Plate Thickness:	<input type="text" value="2"/> mm
Scaling Factor Gas Volume:	<input type="text" value="1"/> [-]

▼ Membrane Assembly

Membrane Thickness:	<input type="text" value="0.02"/> mm
Scaling Factor Active Membrane Area:	<input type="text" value="1"/> [-]

Figure 2. Design parameters used for fuel cell system.

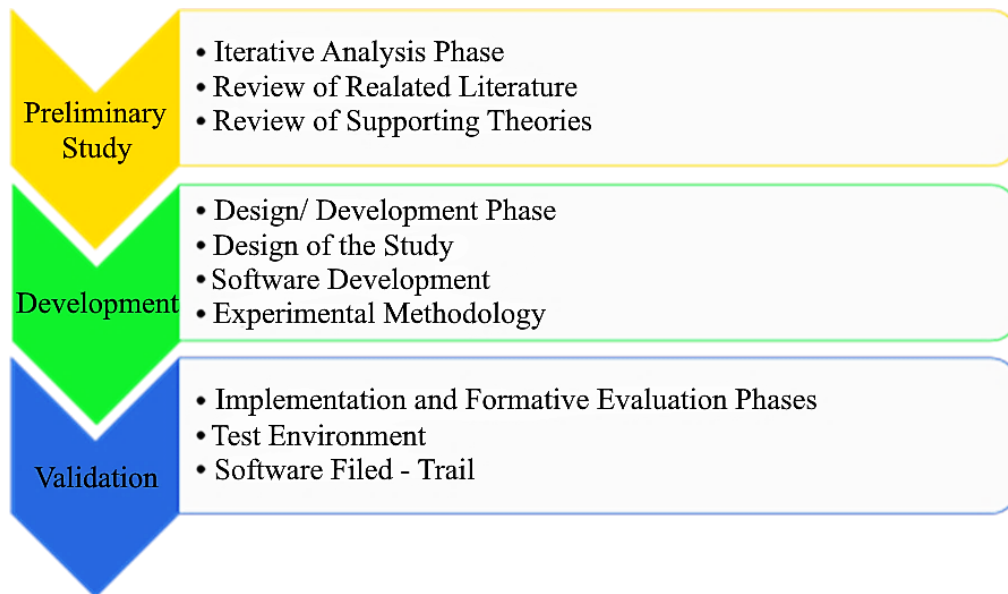


Figure 3. Research methodology.

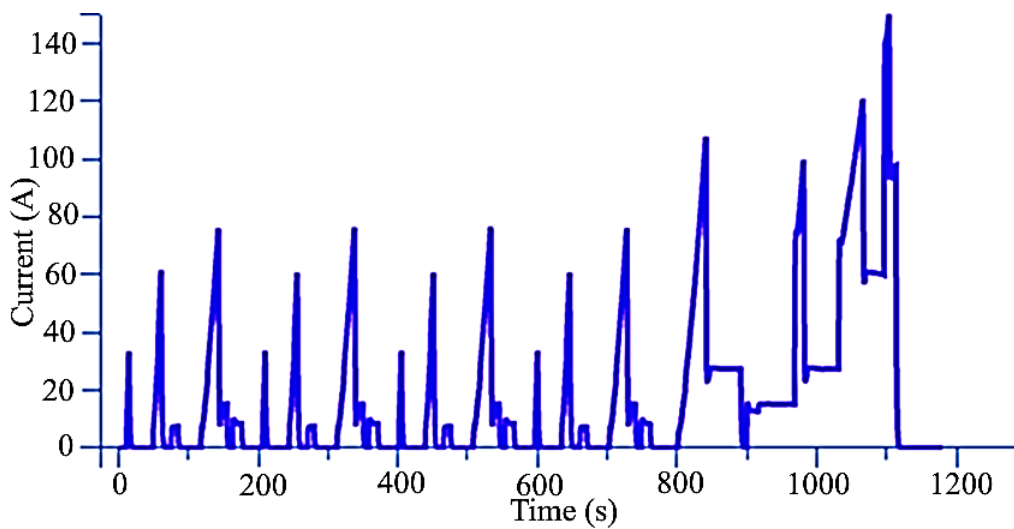


Figure 4. Fuel cell stack current vs Time.

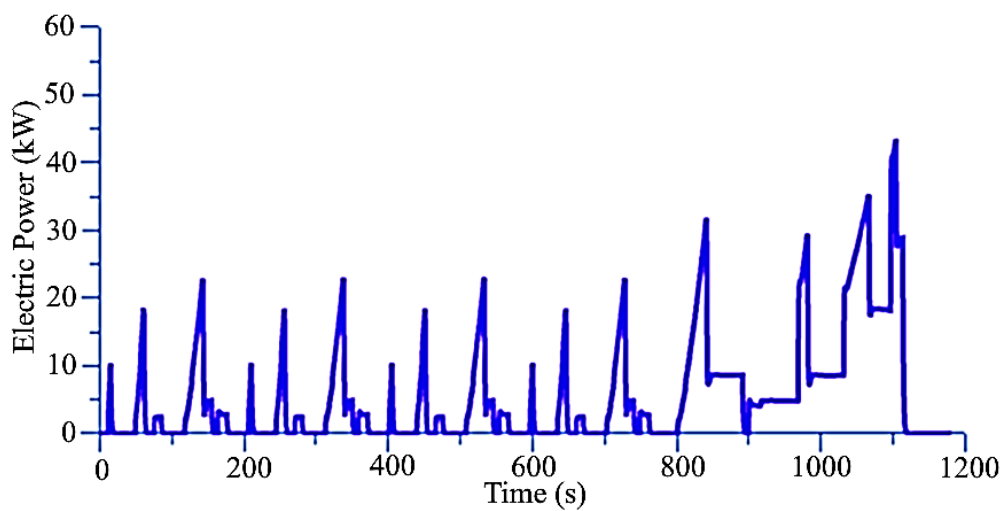


Figure 5. Fuel cell stack power vs Time.

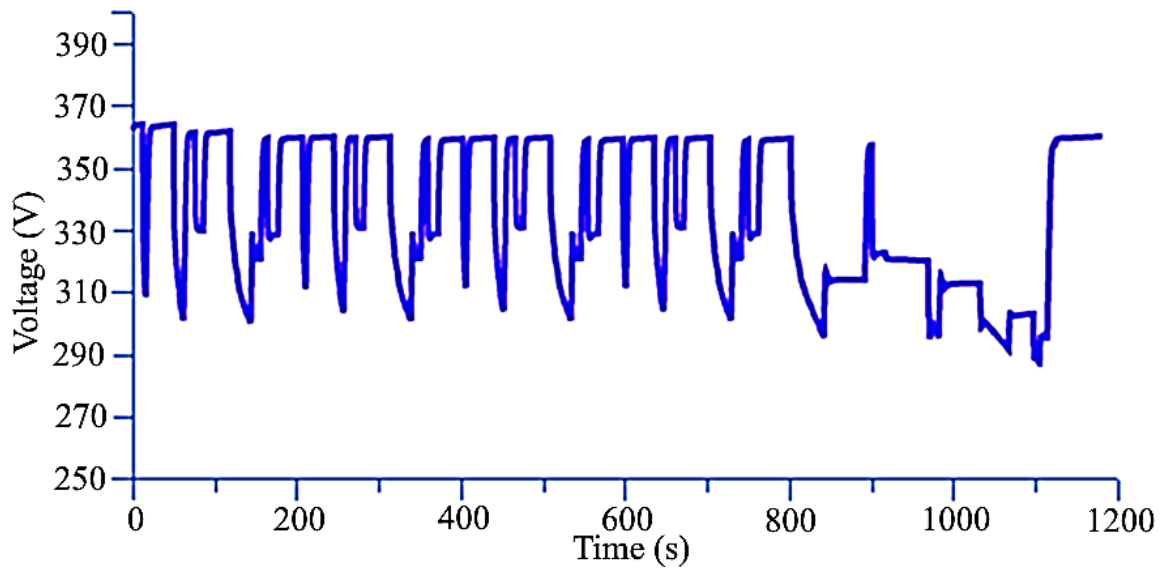


Figure 6. Fuel cell stack voltage vs Time.

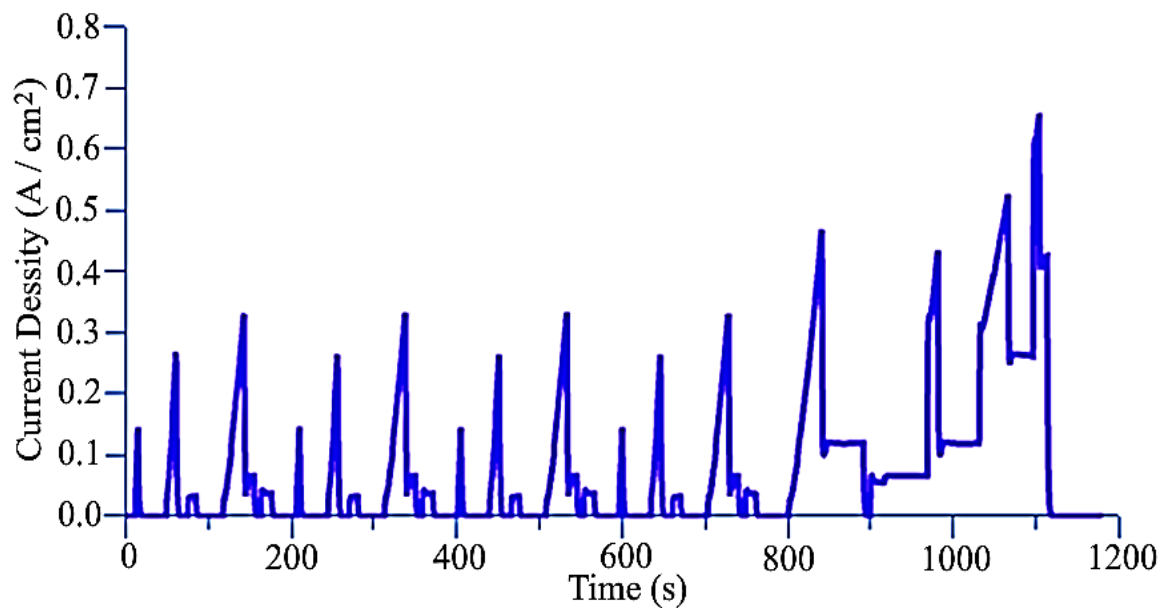


Figure 7. Fuel cell stack current density vs Time.

The current density profile closely followed the dynamic load profile, demonstrating the fuel cell stack's excellent responsiveness. Importantly, the system maintained stable operation with minimal current oscillations, even during rapid load transitions. This behavior underscores the effectiveness of the control strategy and the robustness of the power conditioning system. Moreover, the observed current density values fall within the optimal operating range for PEM fuel cells, ensuring high efficiency while minimizing degradation risks. Sustained operation at or near peak current density without significant voltage drop or ripple further confirms the system's load following capability and electrochemical stability.

Power density, defined as the power output per unit active area of the fuel cell, is a key performance metric that reflects the system's ability to deliver energy efficiently within a compact footprint. In this study, the PEM fuel cell stack was evaluated under dynamically varying load conditions to assess its power density characteristics. Figure 8 presents the power density profile over time. The fuel cell stack achieved a peak power output of 45 kW, with an active cell area of 230 cm², resulting in a maximum

power density of 5000 W/m². This value indicates a high-performance operation, suitable for automotive and medium-duty applications where space and weight constraints are critical. Throughout the dynamic load cycles, the power density varied in response to changing current and voltage levels. During low-load conditions, the power density remained modest, while under high-demand scenarios, it increased significantly. Importantly, the system maintained stable power delivery with minimal ripple, even during rapid transitions, demonstrating the effectiveness of the control and power management systems. The observed power density values are consistent with those reported in high-efficiency PEM fuel cell systems. The ability to sustain high power density without compromising voltage stability or inducing thermal stress highlights the robustness of the stack design and the efficiency of the thermal and electrical management strategies.

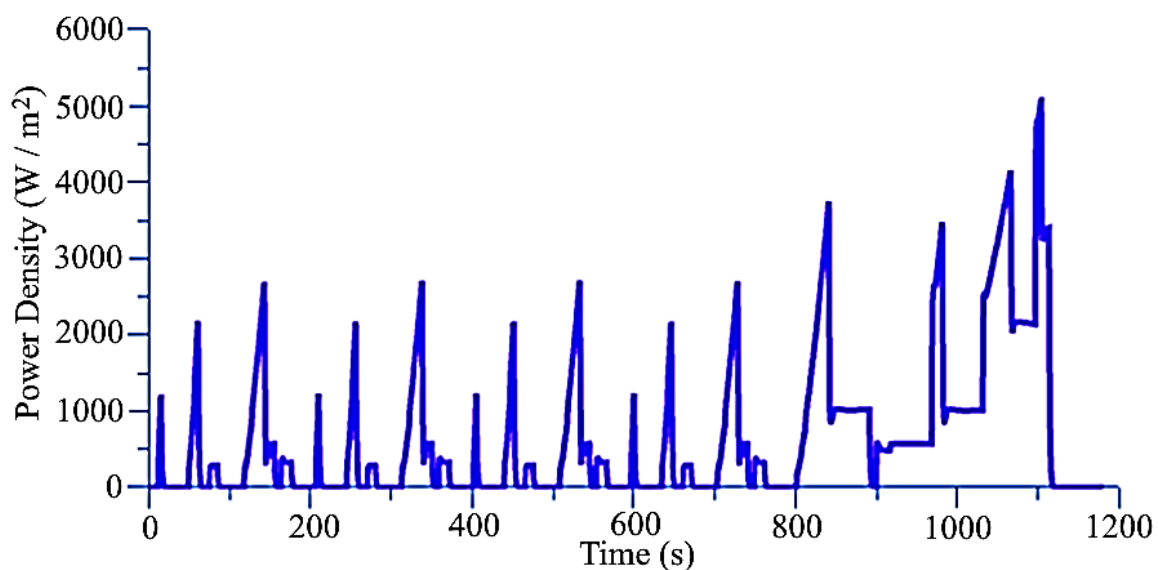


Figure 8. Fuel cell stack power density vs Time.

Hydrogen consumption in fuel cell vehicles (FCVs) varies based on factors such as vehicle model, driving conditions, and the efficiency of the fuel cell system. Naturally, as the power output of the fuel cell increases, so does hydrogen usage, since greater energy input is required to meet higher power demands. Figure 9 illustrates the mass flow rate of hydrogen gas over time. Under dynamic driving conditions such as those encountered in urban or mixed traffic vehicle speed changes frequently. These fluctuations directly influence the power demand on the fuel cell, resulting in variable hydrogen consumption. This pattern is evident in time-series plots of hydrogen usage, where consumption peaks typically align with acceleration or high-speed driving, while dips correspond to deceleration or idling periods.

Figure 10 illustrates the variation of compressor inlet air mass flow rate over time. In fuel cell vehicles (FCVs), this parameter plays a vital role in determining the performance of the proton exchange membrane fuel cell (PEMFC). As the power output of the fuel cell increases, the demand for oxygen rises accordingly, leading to a higher air intake rate through the compressor.

Figure 11 presents the compressor outlet air mass flow rate over a 1200-second dynamic driving cycle. The flow rate fluctuates between 0.5 and 90 kg/hr, mirroring variations in the vehicle's power demand. These fluctuations are closely tied to the oxygen requirements of the fuel cell, which increase during periods of acceleration and high-speed cruising. In fuel cell vehicles (FCVs), the compressor outlet air flow rate is a critical parameter, ensuring that the fuel cell stack receives adequate oxygen to maintain efficient electrochemical reactions. Higher flow rates are observed during power-intensive phases such as acceleration or highway driving, while lower rates occur during idling or low-speed operation, contributing to energy conservation.

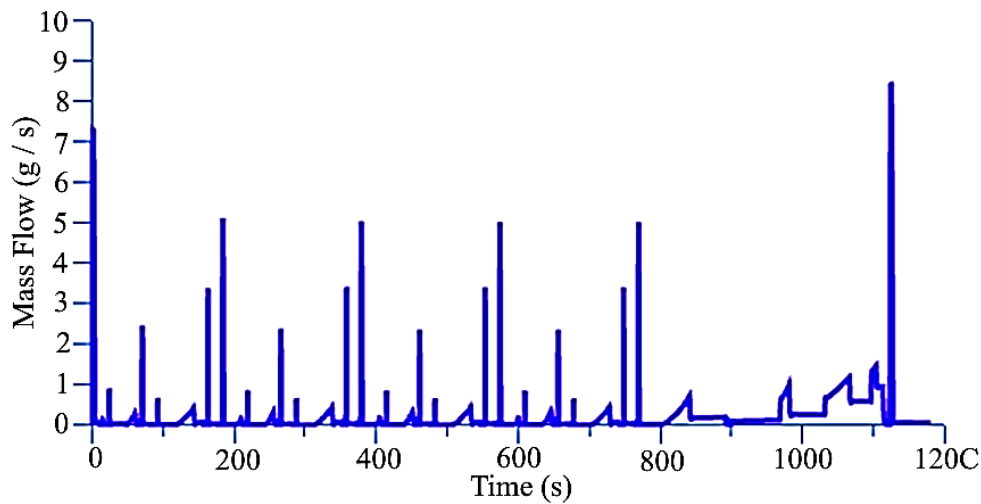


Figure 9. Hydrogen gas mass flow vs Time.

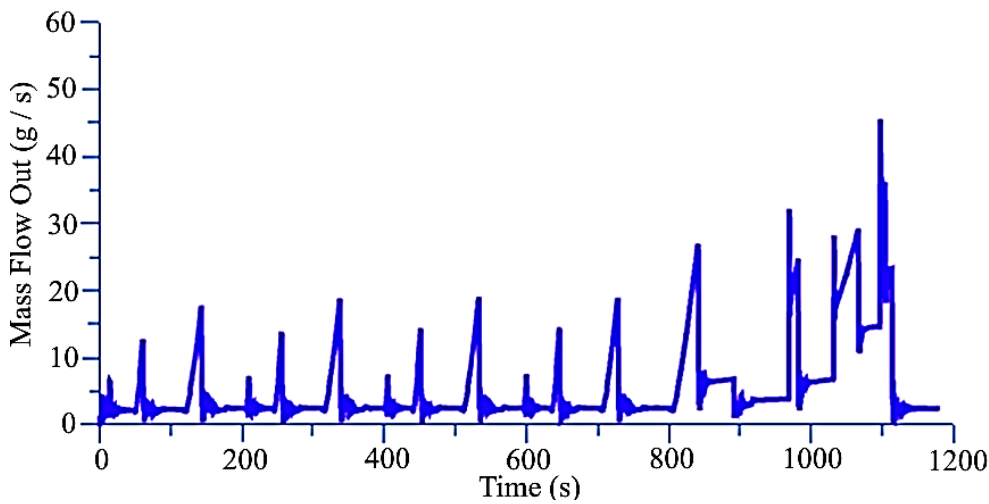


Figure 10. Compressor inlet air mass flow rate vs Time.

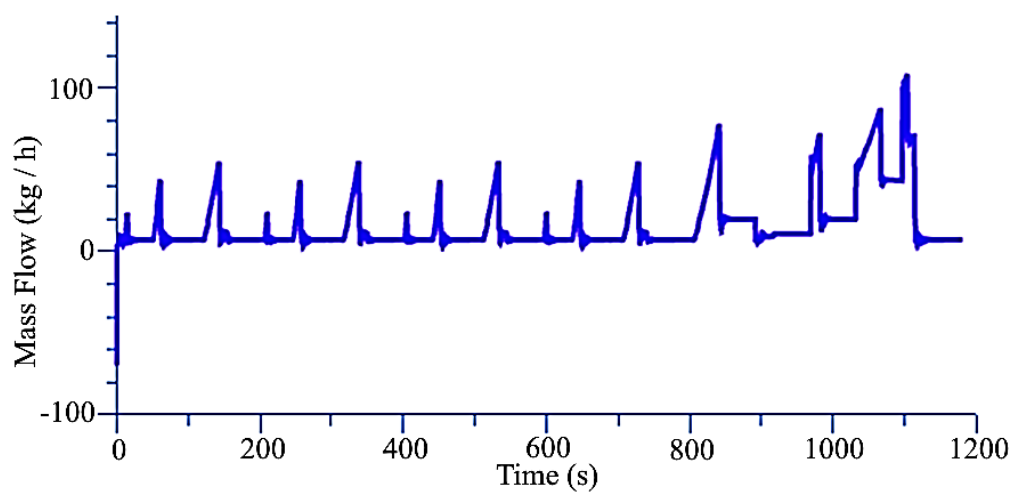


Figure 11. Compressor outlet air mass flow rate vs Time.

The compressor outlet pressure is a crucial parameter that ensures the fuel cell stack receives air at the appropriate pressure to sustain efficient operation. FCVs commonly use centrifugal compressors due to their compact design and high efficiency. The outlet pressure dynamically adjusts with changes

in compressor speed and vehicle power demand. During acceleration or high-load scenarios, the compressor ramps up to increase outlet pressure and meet elevated oxygen requirements. Conversely, during idle or low-load conditions, the pressure is reduced to conserve energy and protect the fuel cell stack from over-pressurization. Figure 12 illustrates the compressor outlet pressure over time. In fuel cell vehicles (FCVs), this pressure is governed by the compressor's pressure ratio, which typically ranges from 1.2 to 1.5. This corresponds to outlet pressures between 150 and 300 kPa, depending on inlet conditions and compressor speed. Maintaining an optimal outlet pressure is essential for two key reasons: To prevent oxygen starvation during high-load conditions and to avoid unnecessary parasitic losses caused by over-compression.

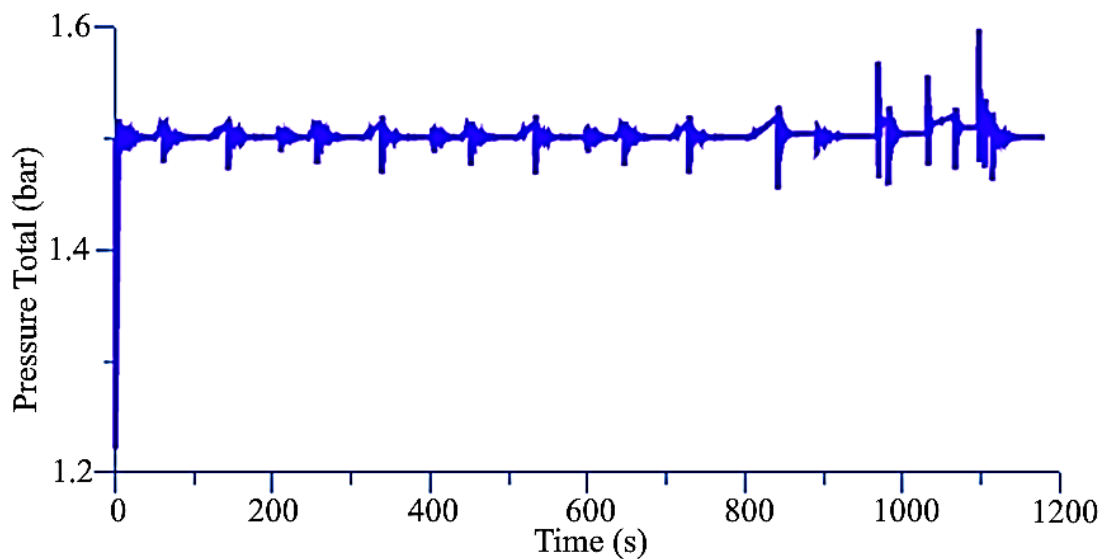


Figure 12. Compressor outlet pressure vs Time.

Figure 13 displays the variation in compressor efficiency over time. In a fuel cell system, compressor efficiency measures how effectively the compressor converts electrical input energy into mechanical work to compress air. This efficiency is a critical factor in determining the overall performance of the fuel cell system. A key metric used to evaluate this performance is the isentropic efficiency, which for centrifugal compressors commonly used in FCVs typically ranges between 60% and 75%. Compressor efficiency is influenced by several factors, like pressure ratio, rotational speed and inlet temperature.

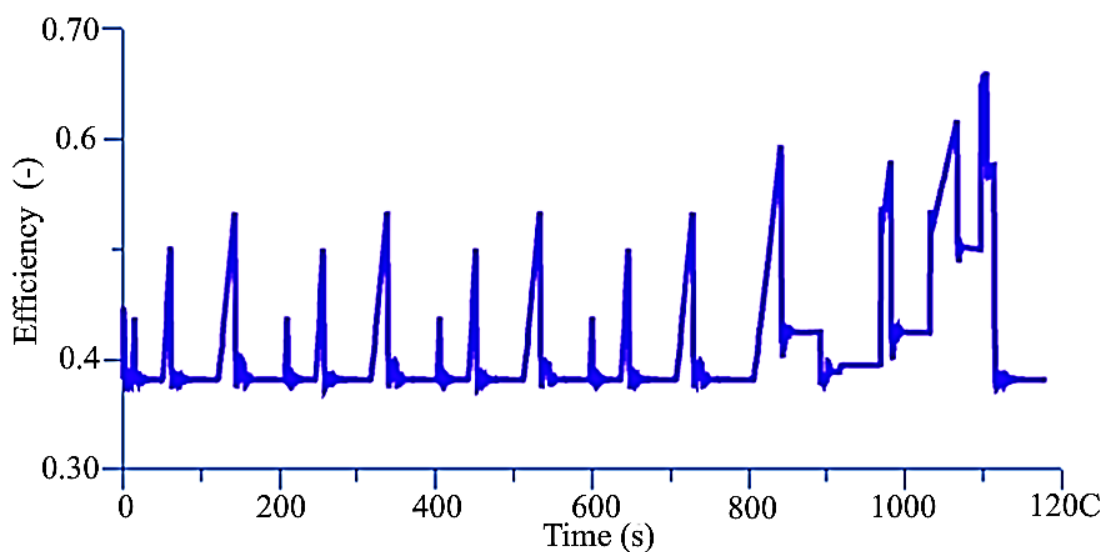


Figure 13. Compressor efficiency vs Time.

Higher pressure ratios increase the work required for compression and generate more heat, which can reduce efficiency. Hence, the pressure ratio is set at optimized condition for better efficiency. Efficiency peaks at an optimal speed; operating too far above or below this point leads to performance losses. In addition, air density and the amount of work needed for compression higher temperatures generally reduce efficiency, hence it is also optimized. Overall, maintaining optimal compressor efficiency is essential for minimizing energy losses and ensuring the fuel cell operates effectively across varying driving conditions.

Figure 14 shows compressor speed vs time. As compressor speed increases, the air mass flow rate increases linearly. This reflects the behavior of a centrifugal compressor, where higher rotational speeds result in greater air intake and delivery to the fuel cell stack. The flow rate starts around 0.5 kg/hr and reaches nearly 90 kg/hr around 100,000 RPM in this simulation. A direct relationship was observed between compressor rotational speed and outlet air mass flow rate. This trend confirms that higher compressor speeds are required to meet increased oxygen demand during high-power operation.

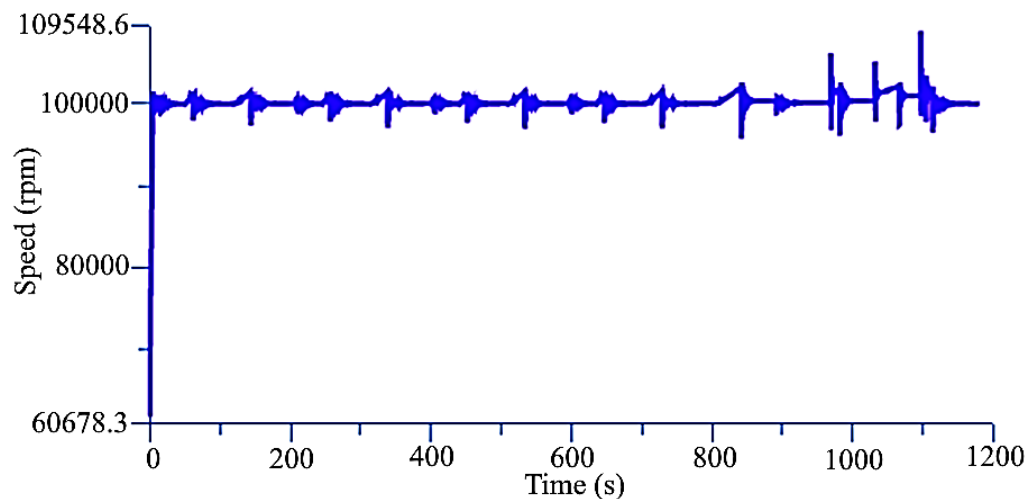


Figure 14. Compressor speed vs Time.

The intercooler is used to cool the compressed air exiting the compressor before it enters the fuel cell stack. Cooling the air increases its density, improving the oxygen supply and fuel cell efficiency. It also helps maintain membrane hydration and prevents thermal degradation of the fuel cell components. Figures 15 and 16 shows intercooler inlet and outlet temperature vs time. During transient load changes, the intercooler must respond quickly to fluctuating air temperatures. Delays in thermal response can lead to temporary efficiency losses or membrane dehydration.

For the selected compressor design, an air outlet temperature of around 120°C is achieved. However, with the use of the intercooler system, the air outlet temperature is further reduced to 33 °C. Overall, about 55–65 % of the intercooler efficiency for all surface area conditions is accomplished based on these studies. The intercooler achieved a temperature reduction depending on the compressor outlet temperature and ambient conditions. This cooling effect significantly improved the air density.

Figure 17 shows humidifier mass flow rate over the time. The calculated air mass flow rate of 8.4 kg/h is within the expected range for medium-scale PEM fuel cell systems. This flow rate ensures sufficient oxygen supply and effective humidification, which is essential for maintaining membrane hydration and minimizing ohmic losses. The increase in humidifier relative position confirms effective moisture transfer. Stable air flow supports consistent fuel cell performance and prevents membrane drying or flooding. However, variations in ambient conditions can affect air density and humidity control. Hence, precisely control of flow rate and temperature is maintained to avoid performance degradation also.

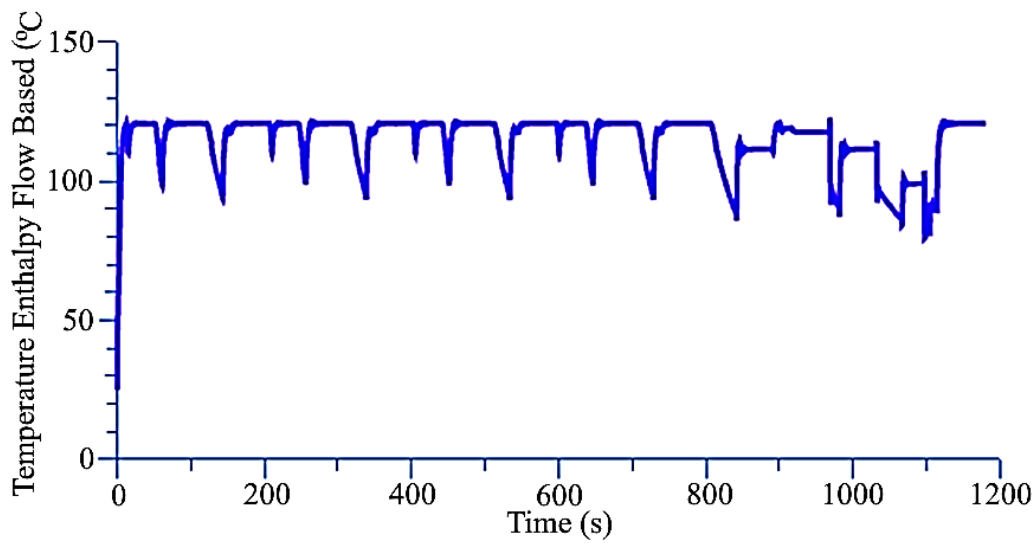


Figure 15. Intercooler inlet temperature vs Time.

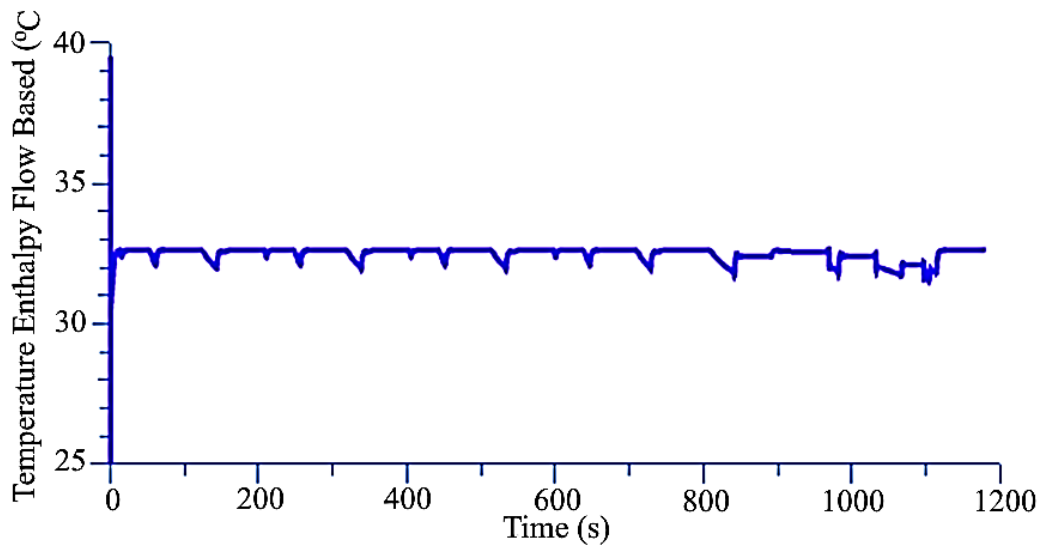


Figure 16. Intercooler outlet temperature vs Time.

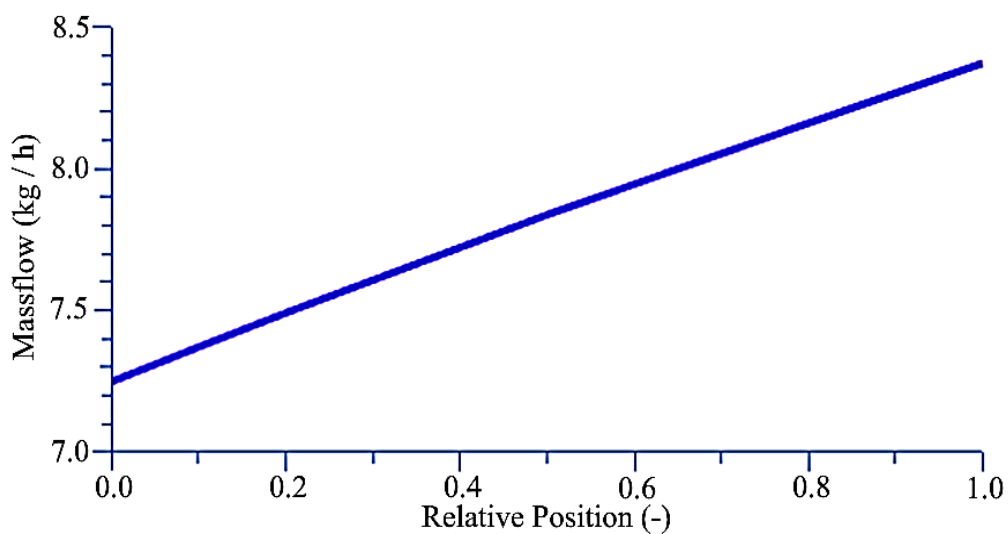


Figure 17. Humidifier mass flow rate vs Time.

Figure 18 shows humidifier temperature over the time. In PEM fuel cell systems, the temperature of the air passing through the humidifier plays a crucial role in determining the moisture-carrying capacity of the air. This section analyzes the temperature change of air across the humidifier and its impact on humidification efficiency and fuel cell performance. The air temperature increased from 35 °C to 65 °C as it passed through the humidifier. This temperature rise is primarily due to the heat exchange process within the humidifier, which is often designed to preheat the air to enhance its moisture absorption capacity.

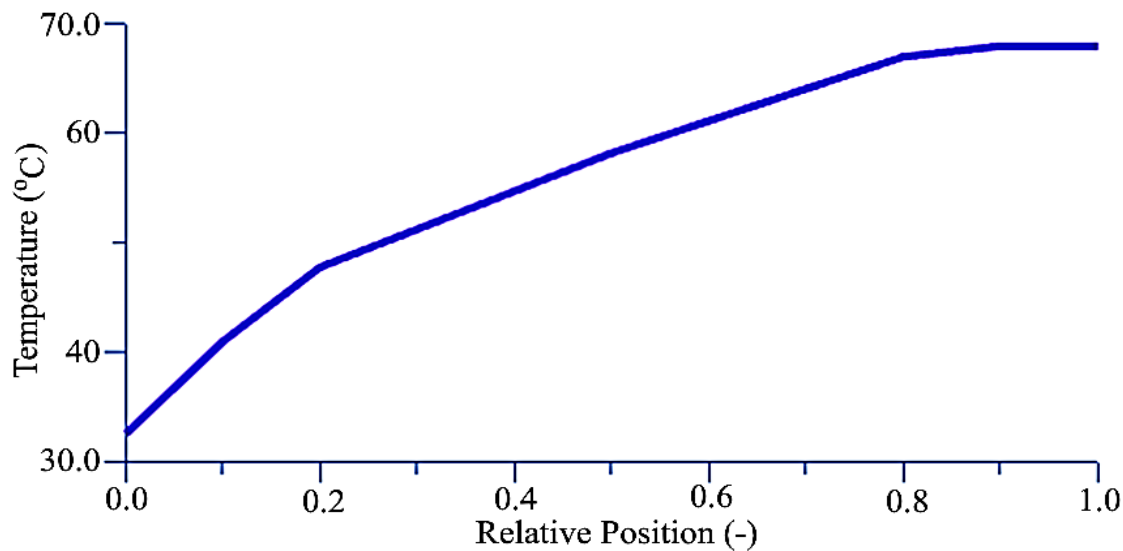


Figure 18. Humidifier temperature vs Time.

CONCLUSIONS

Using the AVL CRUISE™ M simulation platform, a comprehensive PEM fuel cell model was developed and evaluated under a representative truck duty cycle. The simulation results revealed that a configuration consisting of 370 cells with a stack area of 230 cm² achieved a peak power output of 45 kW.

By fine-tuning critical operational parameters and integrating advanced control strategies, the fuel cell system can be effectively adapted to meet the demands of specific applications, resulting in enhanced energy output and reduced degradation. Notably, optimizing air compressor operation significantly improves power output, particularly at high current densities around 0.6 A/cm².

In addition, precise humidification and thermal management are essential for maintaining membrane hydration, which is crucial for consistent and efficient performance. Dynamic simulations further provide valuable insights into the system's transient behavior during load variations an important factor for real-world deployment scenarios.

Overall, this study delivers a comprehensive understanding of the 45 kW PEMFC system's capabilities, supporting faster and more cost-effective development for commercial applications. These performance simulations are vital for improving the efficiency, reliability, and operational lifespan of PEMFC systems

Nomenclature

Bop	: Balance of plant
PEM	: Proton exchange membrane
MEA	: Membrane electrode assembly
GDL	: Gas diffusion layer

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

Credit Author Statement

- *Karthikeyan Subramanian*: Conceptualization, Writing-original draft & editing Supervision, Data curation.
- *Venkateshkumar Velmurugan*: Simulation.
- *Parthiban Sivagurunathan*: Formal analysis, writing-review.

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