

Performance test of a hydrogen-powered solid oxide fuel cell system and its simulation for vehicle propulsion application

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ARTICLE INFO

Handling Editor: Panos Seferlis

Keywords:

Solid oxide fuel cell
Hydrogen-powered
Vehicle propulsion
Fuzzy control

ABSTRACT

Solid oxide fuel cells (SOFC) have not received enough attention as a power source in the transportation sector. However, with the development of the technology, its advantages over other types of fuel cells, such as fuel flexibility and high energy efficiency, have made SOFC an interesting option. The present study aims at simulation and experimentally validation of the performance of a hydrogen-powered SOFC in an automotive application. A 6 kW SOFC stack is tested, and its model is integrated into a series hybrid electric vehicle model. A fuzzy controller is designed to regulate the charging current between the battery and the SOFC in the vehicle model. Experimental tests are also conducted in a few cases on the SOFC based on the simulation results. The performance of the real SOFC stack is then analysed under dynamic loads to see how the desired current is provided in practice. The results demonstrate a good performance of the SOFC stack under variable load conditions.

Nomenclature

Abbreviation (Description)		w^*	Rotational velocity of the motor
ASR	Area-specific resistance	V_{speed}	Vehicle's speed
ASV	Automatic shut-off valve	R_w	Wheel radius
DC EL	Electronic load	G	Gear ratio
EMS	Energy management system	F_t	Tractive force
EV	Electric vehicle	T_{avl}	Available torque
FC	Fuel cell	η_m	Electric motor efficiency
HB	Hot box	η_{gear}	Gearbox efficiency
HEV	Hybrid electric vehicle	F_g	Road gradient
MFC	Mass flow controller	F_{roll}	Rolling resistance
OCP	Open circuit potential	F_{aero}	Aerodynamic drag
PEM	Proton-exchange membrane	F_b	Braking force
R-SOFC	Reversible-SOFC	V_{OC}	Voltage source
SOC	State of charge	R_O	Ohmic resistance
SOFC	Solid oxide fuel cell	R_1	Polarisation resistance

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TC	Thermocouples	I_L	Current load
WLTP	World harmonized light vehicle test procedures	$I_{Cell,dem}$	Cell current demand
Symbol (Description)		P_{demand}	Power Demand
E_{nerst}	Open circuit voltage	M_{AB}	Mixture Molar Mass
V_{act}	Activation voltage	δ_{O_2}	Diffusion coefficient ratio
V_{conc}	Concentration voltage	D_A^{eff}	Effective Diffusion Coefficient
V_{ohm}	Ohmic Voltage	$D_{A,knudsens}$	Knudsen Coefficient
E_0	Standard reversible cell potential	Unit (Description)	
R	Universal gas constant	K	Kelvin
P_i	Pressure i: variable	A	Ampere
F	Faraday's constant	kW	Kilowatt
T	Operating temperature	kWh	Kilowatt-hour
i	Current density	L/min	Liter per minute
n	Number of electrons transferred	Kg	Kilogram
$i_{L,i}$	The limiting current density i: variable	m	Meter
i_{fc}	Fuel cell current		

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U_{fi}	Rates of consumption <i>i</i> : variable	V	Volt
T_{req}	Required torque	Ah	Ampere hour
Acc	Acceleration command	C	Celsius
$T_{m,max}$	Maximum torque	°	Degree
P_{req}	Requested power	m/s	Meter per second

1. Introduction

The energy demand in the world has been increasing rapidly in the last decades. Since it is predicted that energy resources will not be able to meet this demand, the tendency towards alternative energy and renewable sources is increasing. Renewable energy resources are witnessing a significant upward trend, reflecting a global shift towards more efficient energy utilization and diverse strategies (Zailani et al., 2015). This shift is not only aimed at energy conservation and reduced consumption but also it addresses the critical issue of environmental pollution. In the lights of the automotive industry, petroleum and its derivatives, which are used as fuel, account for most of that pollution. In line with these objectives, there has been a surge in the research, development, and popularization of various electric vehicles (EVs) worldwide (Habib et al., 2020; Lin et al., 2023; Yin et al., 2023). These vehicles represent a promising step towards a more sustainable future. However, despite the advantages that EVs offer, they do face certain obstacles including a restricted driving range due to the low energy density of batteries, prolonged charging times, and an inadequate network of charging facilities. These shortcomings highlight the need for continued innovation and infrastructure development in the realm of EVs. To overcome the disadvantages of EVs, one of the solutions, which has been proposed for the next generation of vehicles, is fuel cell technology (Boldrin and Brandon, 2019; Manoharan et al., 2019; Ferná et al., 2022).

Fuel cell vehicles have notable advantages that can be attributed to their featured properties, including but not limited to their high energy conversion efficiency, quick fuel refilling time, extensive cruising range, and zero emissions. The utilization of fuel cell vehicles, alternative energy sources, is widely regarded as a promising alternative to traditional fossil-fuelled transportation methods (Yue et al., 2021; Ehsani et al., 2018). There are several types of fuel cells in the market. Among these, A well-known type is the proton-exchange membrane (PEM) fuel cell, which stands out due to its unique characteristics and applications (Mekhilef et al., 2012). However, despite its advantages, a PEM fuel cell only works with pure hydrogen (DOE Energy Efficiency and Renewable Energy Information Centre, 2016). Additionally, pure hydrogen needs to be stored at 350–700 bar, and this imposes additional safety restrictions (Zheng et al., 2012).

Another type of fuel cell is called solid oxide fuel cell (SOFC), which

is the main focus of this study. SOFCs are particularly interesting as they can operate using a wide variety of fuels such as natural gas, biogas, syngas, ethanol, ammonia, and hydrogen (DOE Energy Efficiency and Renewable Energy Information Centre, 2016; Chen et al., 2019; Shcheklein and Dubinin, 2021). This is unlike PEM fuel cells that can only run on hydrogen. At the same time, SOFCs have an integrated fuel converter to convert carbonaceous fuels to hydrogen (Ilbas et al., 2022; de Souza et al., 2021). This feature of SOFC eliminates the need to store hydrogen in the vehicle at high pressure (Gó et al., 2023). The other advantages of SOFC are its higher efficiency compared to PEM, and the possibility of energy regeneration (DOE Energy Efficiency and Renewable Energy Information Centre, 2016; Ni et al., 2008). In fact, the fuel that is used in SOFC can be regenerated through reversible reactions (electrolysis mode) and electricity generation (Fuel Cell Mode). Thanks to this reversible characteristic, SOFC is also called Reversible SOFC (R-SOFC) or Solid Oxide Electrolyser (SOEC) (Santhanam et al., 2017).

Due to the advantages mentioned above, it is promising to use SOFC as a propulsion system in vehicles. While such vehicles are not yet available on the market, there are a few studies in the literature where SOFC is the main propulsion system. One of the first examples in this field is the work by Brett et al. (2006), which combines a SOFC with a Zebra battery to provide an energy buffer. That approach allows the SOFC to operate continuously, avoiding its long startup times. Since both the SOFC and the Zebra battery are high-temperature systems, it was initially believed that this similarity would simplify integration. However, a challenge arises because these components continuously generate heat, even when the vehicle is stationary. After that, in 2016, Nissan Motor Corporation introduced the first SOFC vehicle as a prototype. That vehicle has a range of more than 600 km and runs on bio-ethanol fuel. It thus offers a solution to the explosive effect of hydrogen gas and the vehicle has great potential for countries such as Brazil and Thailand, where biofuels are widely used. Moreover, it eliminates the need to develop the infrastructure against the PEM FC vehicle, which can only run on hydrogen (Nissan Motor Corporation, 2016; Lucas, 2016). Similarly, the research by Velandia and Abel (Velandia et al., 2021) supports this view. They conducted a life cycle analysis on light-duty SOFC and PEMFC vehicles in Brazil. That study demonstrated that SOFC vehicles are beneficial for electrification and particularly for the use of biofuels in the transportation sector. The advantage of these vehicles is that they can utilize the existing biofuel infrastructure, eliminating the need to construct a separate hydrogen infrastructure. Furthermore, Gonçalves et al. (de Oliveira Gonçalves et al., 2021) have highlighted the feasibility of using ethanol-based SOFC vehicles in Brazil, where the existing biofuel infrastructure makes SOFC a practical and scalable solution, eliminating the need for a dedicated hydrogen infrastructure. Furthermore, a life cycle analysis on ammonia-fuelled SOFC vehicles by Liao et al. (2023) shows that

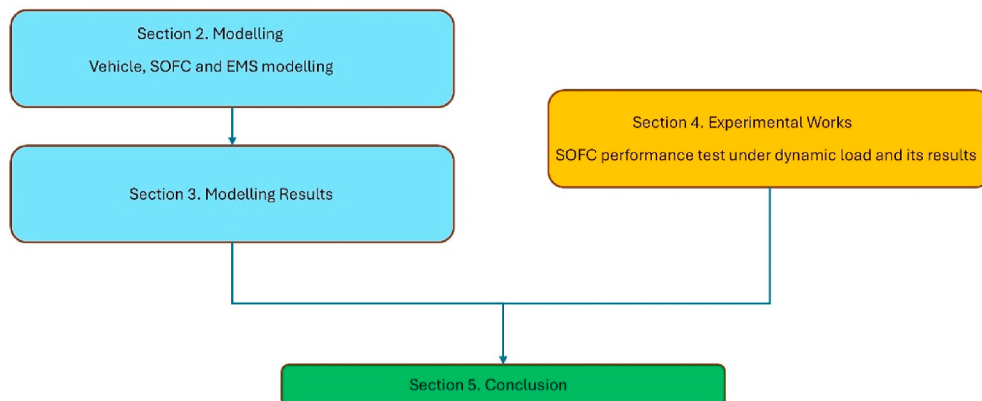


Fig. 1. Flow chart of the structure of the paper.

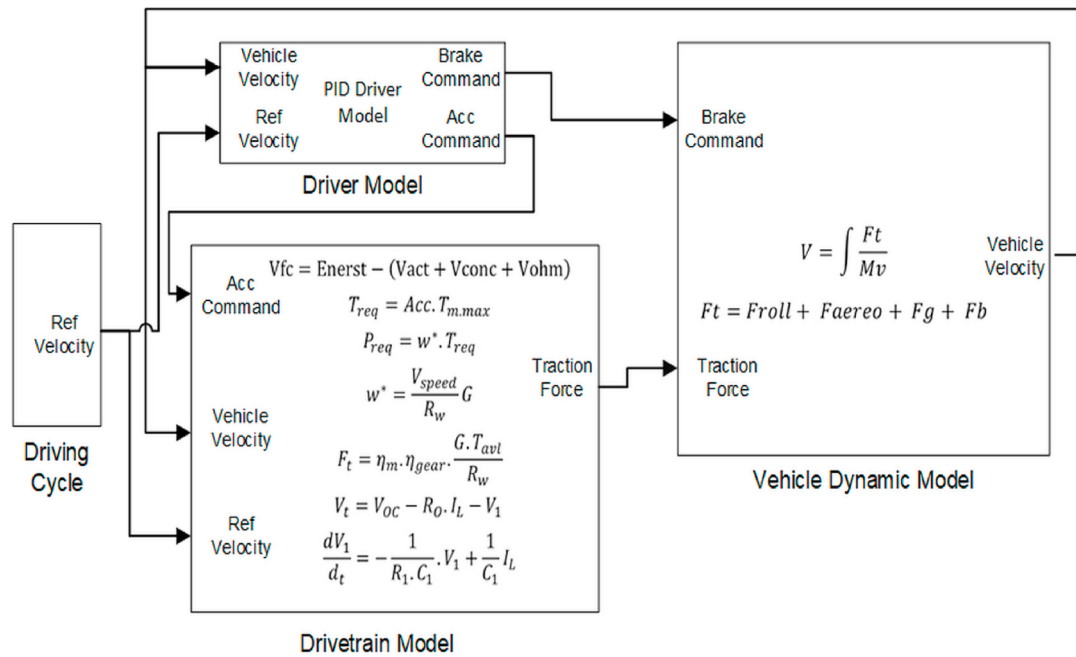


Fig. 2. MATLAB/Simulink model of the SOFC vehicle.

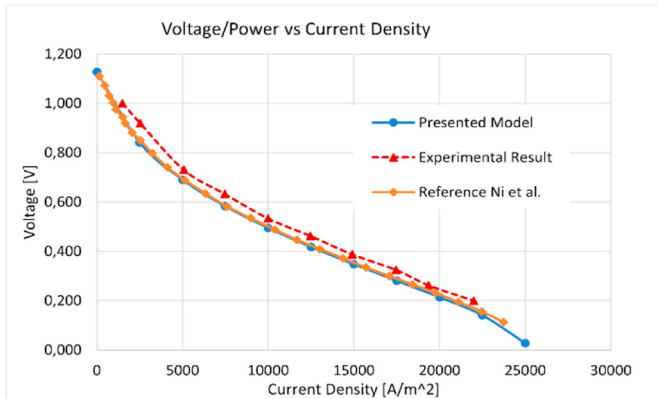


Fig. 3. Comparison between the designed SOFC model's voltage-current graph versus another model and experimental data in the literature.

ammonia could be a sustainable alternative fuel, particularly in regions where hydrogen is not easily accessible, combining low emissions with high efficiency. In another study in the literature, Bessekon et al. (2019), SOFC has been used as a range extender system. A 12 kW SOFC module is integrated with a partial oxidation fuel reformer into a modified Nissan Leaf Electric Vehicle model. This integration resulted in the vehicle achieving impressive drive ranges: 264 km when using CNG, more than 700 km with LNG, and 823 km when using LPG. This is a remarkable improvement compared to the original model's 170 km range. Likewise, Chehrmonavari et al. used an SOFC for the range extender (Chehrmonavari et al., 2023). Their study demonstrated that hybridising SOFC with internal combustion engines can increase efficiency by over 70%, making it especially suitable for heavy-duty propulsion systems. Another example is the study by Sandrini et al. (2023) in which a hybrid vehicle model is developed using a 3 kW SOFC powered by biomethane and a 30 Ah battery pack, suited for door-to-door waste collection vehicles in a fleet with fixed routes. The

Table 1

Parameters of the modelled SOFC (Ni et al., 2007; Wu et al., 2019; Yang et al., 2020).

Specification	Parameter	Value	Unit
Faraday Constant	F	96487	$C. mol^{-1}$
Gas Constant	R	8314	$J. (kmol. K)^{-1}$
Temperature	T	973	K
Cell area	A	0.018	m^2
Operation pressure	P	1×10^5	Pascal
Current density		0–25000	A/m^2
Pre-exponential coefficient	γ_{an}	1.34×10^{10}	$A m^{-2}$
Pre-exponential coefficient	γ_{cat}	2.05×10^9	$A m^{-2}$
Anode Activation Energy	E_{an}	1×10^5	J/mol
Cathode Activation Energy	E_{cat}	1.2×10^5	J/mol
Porosity anode	η_{an}	0.48	
Porosity cathode	η_{cat}	0.27	
Tortuosity anode	ζ_{an}	3	
Tortuosity cathode	ζ_{cat}	3.5	
Average pore diameter	r	1.15×10^{-7}	m
Anode thickness	da	1×10^{-3}	m
Cathode thickness	dc	2×10^{-5}	m
Electrolyte thickness	L	8×10^{-6}	m
Pressures of fuel	P_{fuel}	1.5×10^5	Pascal
Pressures of air	P_{air}	1×10^5	Pascal
Percentages of hydrogen in the fuel	x	99.95	%
Percentages of oxygen in the air	y	21.1	%

Table 2

Nissan Leaf parameter.

Specification		Value	Unit
Vehicle Mass	Mv	1500	Kg
Wheel's radius	R_w	0.316	M
Gear ratio	G	7.94	-
Electric motor and Inverter efficiency	η_m	0.88	-
Vehicle frontal area	A_f	2.27	m^2
Gearbox efficiency	η_{gear}	0.97	-

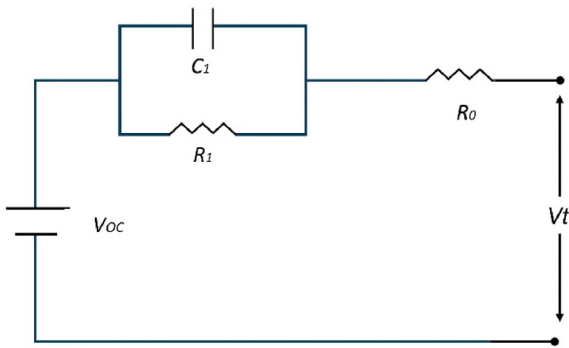


Fig. 4. Thevenin battery model.

Table 3
Specification of the battery pack.

Specification	Value	Unit
Number of cells in series	160	
Number of cells in parallel	4	
Battery pack energy	11	kWh
Cell capacity	4.8	Ah
Cell nominal voltage	3.75	V
Cell cut off voltage	2.5	V

authors stated that this layout is ideal for fleet vehicles with pre-determined missions. However, challenges like the fragility and low durability of SOFCs need to be resolved before their practical implementation in real vehicles. Moreover, the issue of the limited life cycle of batteries is highlighted, emphasizing the need for further research to determine their lifespan accurately.

The main difference between this study and the above-mentioned studies in the literature is to investigate whether a SOFC can meet the dynamic current demand of a hybrid car or not. A concept model is developed for it. The model configuration consists of an unplugged Fuel Cell series Hybrid Electric Vehicle (HEV), whose battery is charged only by the FC. The designed HEV model is based on the Nissan Leaf EV model, which is widely used in the literature (Ragone et al., 2021; Fotouhi et al., 2020). A 6 kW SOFC stack is tested, and its model is built and integrated into the vehicle model. Then a fuzzy controller is designed to control the charging current between the traction battery and the SOFC. Thanks to the controller, the battery state-of-charge (SOC) of the EV is kept at the desired level. Finally, the current delivery of the SOFC is validated based on experimental tests. By focusing on the dynamic current response of the SOFC in the HEV configuration, this study addresses a gap in the literature where most previous works have been focused on stationary applications or auxiliary power systems for vehicles. The use of fuzzy logic for energy management further distinguishes this work, providing a balance between adaptability and control in dynamic conditions. Experimental tests were conducted to evaluate the real-time performance of the SOFC system under varying load conditions, verifying its ability to handle rapid changes in power

demand. These tests provided crucial data on the SOFC's current and voltage response, confirming the system's capability to meet the dynamic requirements of automotive applications.

The organization of this paper is shown in Fig. 1. Section 2 includes SOFC modelling, vehicle modelling and Energy Management System (EMS) modelling. Vehicle simulation results are presented in Section 3. Section 4 includes the validation results that demonstrate the SOFC's performance under a dynamic load. Finally, conclusions are presented in Section 5.

2. Modelling

This section includes modelling of the SOFC, the vehicle, and the proposed EMS. The block diagram of the whole simulation model is shown in Fig. 2. The battery, the fuel cell and the EMS models are located inside the drivetrain block.

2.1. SOFC modelling

The optimal performance of a SOFC system can only be achieved when all dynamic factors are considered. The modelling process for the voltage response of the SOFC includes four main parts: (i) the open circuit voltage (E_{nerst}), (ii) the activation voltage (V_{act}), (iii) the concentration voltage (V_{conc}) and (iv) the ohmic losses (V_{ohm}) (O' et al., 2016). In terms of model validation, the SOFC is modelled based on literature and validated based on the previous works presented in (Ni et al., 2007) and according to the data of the stack where the experiments were carried out (Wang, 2024). The model outputs at 1023 K are compared against the reference data to ensure the accuracy of the model. The results, which are shown in Fig. 3, are obtained using parameters listed in Table 1. The comparison between the proposed model of this study and previous data in the literature demonstrates that the model works reliably in the whole range of the current density coming from various operating conditions. The overall output voltage of the SOFC, V_{SOFC} , is expressed as follows in which N_{cell} represents the number of cells.

$$V_{\text{SOFC}} = N_{\text{cell}} (E_{\text{nerst}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}}) \quad (1)$$

The E_{nerst} is calculated using the following equation:

$$E_{\text{nerst}} = E_0 + \frac{RT}{2F} \ln \frac{P_{\text{H}_2} P_{\text{O}_2}^{1/2}}{P_{\text{H}_2\text{O}}} \quad (2)$$

Here E_0 is the standard reversible cell potential, R is the universal gas constant with a value of 8.314 J/mol·K, T is the absolute operating temperature in Kelvin, and F is the Faraday's constant, equal to 96,485 C/mol. The terms P_{H_2} , P_{O_2} , and $P_{\text{H}_2\text{O}}$ represent the partial pressures of hydrogen, oxygen, and water vapour, respectively.

The V_{act} for the anode and cathode are related to the energy barrier that must be overcome for electrochemical reactions to take place. It can be represented by the Butler-Volmer equation:

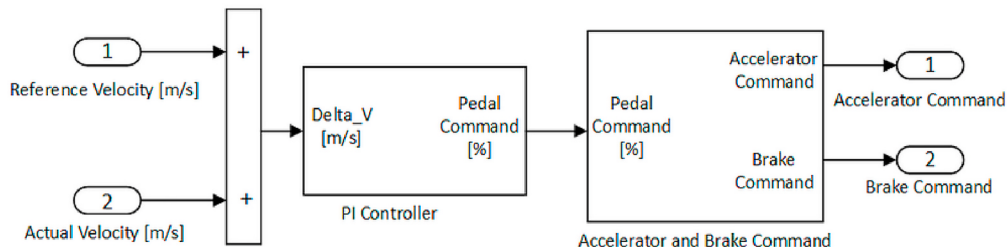


Fig. 5. Block diagram of the driver model.

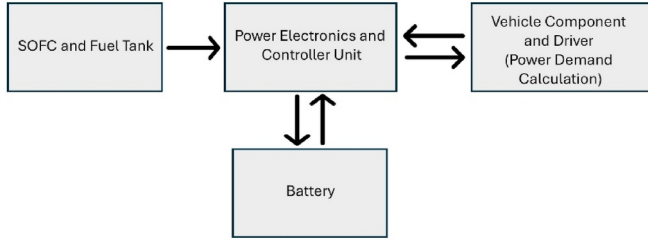


Fig. 6. SOFC vehicle powertrain configuration.

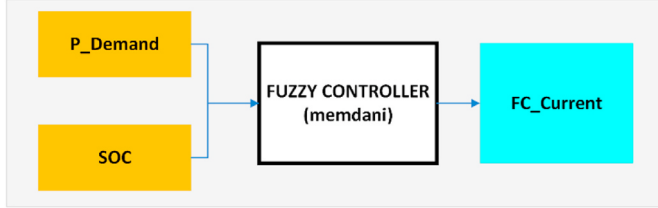


Fig. 7. Schematic of the fuzzy model used for energy management in the SOFC vehicle.

$$V_{act,an,cat} = \frac{2RT}{nF} \ln \left(\frac{i}{2i_0} + \sqrt{1 + \left(\frac{i}{2i_0} \right)^2} \right) \quad (3)$$

In this formula, n refers to the number of electrons transferred during the electrochemical reaction. The current density is represented by i , measured in A/m^2 , and i_0 is the exchange current density, which signifies the rate of the electrochemical reaction when no net current is drawn.

The V_{conc} , also known as diffusion losses, occur as a result of a reduction in reactant concentration at the electrode surfaces at high current densities. These losses can be modelled separately for the anode and cathode. The concentration loss at the anode is expressed as:

$$V_{conc,anode} = -\frac{RT}{nF} \ln \left(\frac{1 - \frac{i}{i_{L,H_2}}}{1 + \frac{i}{i_{L,H_2O}}} \right) \quad (4)$$

At the cathode, the concentration loss is given by:

$$V_{conc,cathode} = -\frac{RT}{nF} \ln \left(1 - \frac{i}{i_{L,O_2}} \right) \quad (5)$$

In these equations, i_{L,H_2} is the limiting current density for hydrogen, i_{L,H_2O} is the limiting current density for water vapour, and i_{L,O_2} is the limiting current density for oxygen. These limiting current densities represent the maximum current that can be drawn from the cell before reactant depletion occurs at the respective electrodes.

V_{ohm} in the SOFC arise from resistance within the cell, both to the flow of ions through the electrolyte and electrons through the electrodes. This resistance can be represented as:

$$V_{ohm} = i_{fc} \cdot ASR \quad (6)$$

Here, i_{fc} represents the current, and ASR refers to the area-specific resistance, a measure of the total ionic and electronic resistances in the cell structure.

Table 1 shows the parameters of the SOFC used in the model. A brief description of the modelling and formulation of the SOFC has been provided above. All of the mathematical equations are presented in Appendix A. Further details related to SOFC modelling can be found in other references (Ni et al., 2007; Padullé et al., 2000; Wu et al., 2019; Yang et al., 2020).

In addition, the rates of consumption of hydrogen (U_{fH_2}) and air (U_{fO_2}) are calculated using the equations below (Souleyman et al., 2009).

$$U_{fH_2} = \frac{6000RTi_{fc}}{nFP_{fuel}V_{fuel}x\%} \quad (7)$$

$$U_{fO_2} = \frac{6000RTi_{fc}}{2nFP_{air}V_{air}y\%} \quad (8)$$

where i_{fc} is the current drawn from the fuel cell in Amperes, n is the number of electrons transferred, typically $n = 2$, P_{fuel} and P_{air} are the absolute pressures of the fuel and air, measured in atmospheres (atm). Finally, V_{fuel} and V_{air} denote the volumetric flow rates of the fuel and air, measured in litres per minute (L/min), and $x\%$ and $y\%$ refer to the molar percentages of hydrogen in the fuel and oxygen in the air, respectively.

2.2. Vehicle modelling

This section presents the development and simulation of a vehicle model under specific driving conditions. Due to the availability of the data in the literature, the Nissan LEAF EV 2015 version is used as the basis for modelling the vehicle. The vehicle model is realized in MATLAB/Simulink environment, as shown in Fig. 2, and the numerical data of Nissan LEAF 2015 are listed in Table 2. The vehicle is equipped with an 80 kW electric motor that generates a maximum torque of 289 Nm. The required torque (T_{req}) is calculated based on the driver's acceleration command (Acc):

$$T_{req} = Acc \cdot T_{m,max} \quad (9)$$

where the $T_{m,max}$ is the maximum torque of the electric motor at each specific speed. The drivetrain model calculates the required power from the required torque. The requested power (P_{req}) is sent to the battery model to determine the available power.

$$P_{req} = w^* \cdot T_{req} \quad (10)$$

The rotational velocity of the motor (w^*) is calculated by taking into account the vehicle's speed (V_{speed}), wheel radius (R_w) and the gear ratio (G).

$$w^* = \frac{V_{speed}}{R_w} G \quad (11)$$

The available battery power is determined by considering the maximum current and voltage drop before reaching the cutoff voltage. Finally, the tractive force (F_t) is updated based on the available torque (T_{avl}). The formula for calculating the efficiency of a vehicle's powertrain is as follows:

$$F_t = \eta_m \cdot \eta_{gear} \cdot \frac{G \cdot T_{avl}}{R_w} \quad (12)$$

where η_m and η_{gear} are efficiency of the electric motor and the gearbox, respectively.

The speed of the vehicle is determined by integrating the acceleration resulting from the superposition of all forces acting on it. This model takes into account the traction force (F_t) and opposing forces caused by road gradient (F_g), rolling resistance (F_{roll}), aerodynamic drag (F_{aero}), and braking (F_b). The total braking force is determined based on the driver's deceleration command. The main parameters of the Nissan Leaf vehicle model are presented in Table 2.

For the battery model, the Thevenin battery model is used as shown in Fig. 4. This model includes an internal voltage source (V_{OC}), an ohmic resistance (R_O), a polarisation resistance (R_1) and a capacitance (C_1). According to Kirchhoff's laws, the battery terminal voltage V_t is derived from the above electrical circuit as a function of the current load I_L .

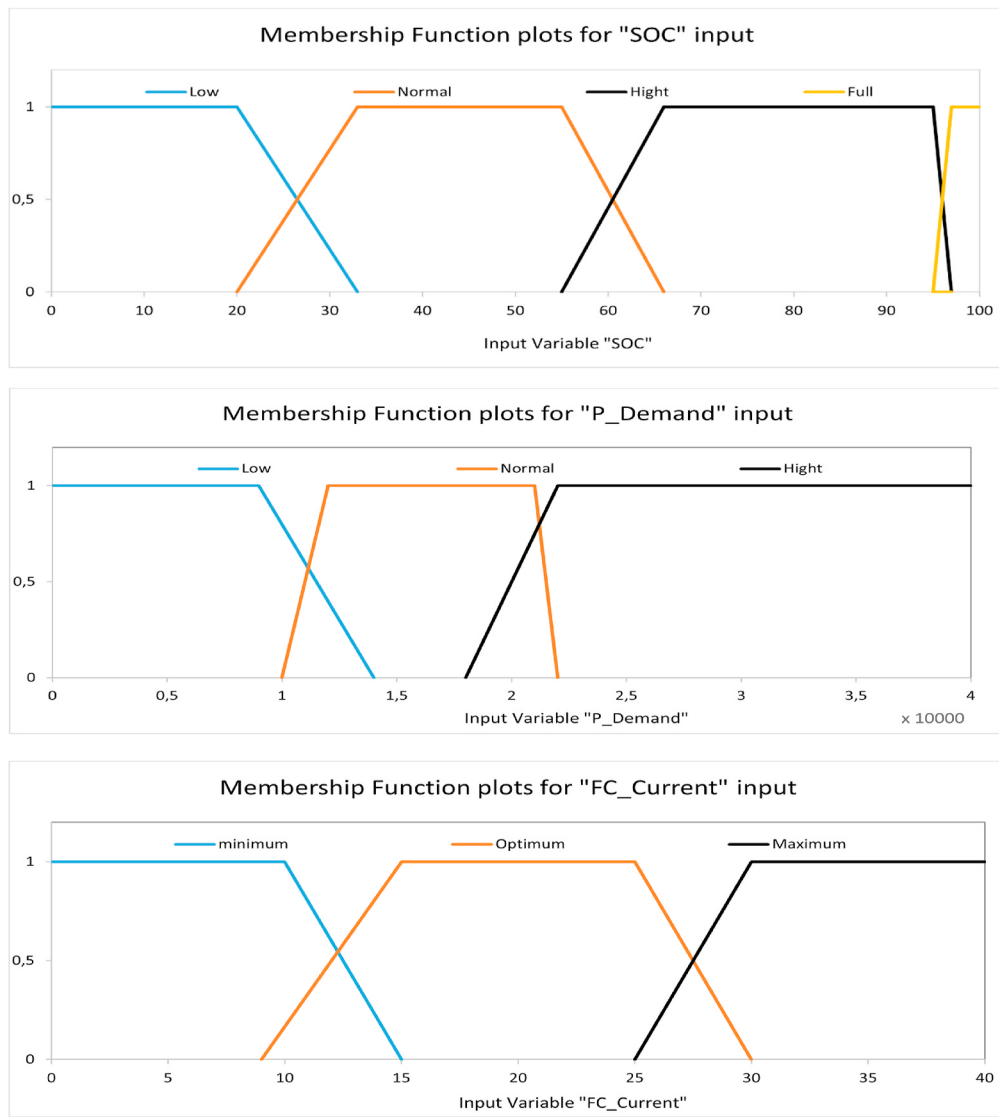


Fig. 8. Membership Functions of the inputs and output of the EMS fuzzy controller.

Table 4

Fuzzy rules used in the EMS model.

Power Demand	Battery SOC	FC Current
High	High	Optimum
High	Normal	Maximum
High	Low	Maximum
Normal	High	Minimum
Normal	Normal	Maximum
Normal	Low	Maximum
Low	High	Minimum
Low	Normal	Optimum
Low	Low	Optimum
–	>%95	0 amp
0-40 KW	%0-%100	0-35 amp

$$V_t = V_{OC} - R_O \cdot I_L - V_1 \quad (13)$$

$$\frac{dV_1}{dt} = -\frac{1}{R_1 \cdot C_1} \cdot V_1 + \frac{1}{C_1} \cdot I_L \quad (14)$$

The battery state-of-charge (SOC) is expressed as a percentage (%) of available charge in the battery as calculated in Eq. 2. 16, with SOC_0 representing the initial state of charge. C_{cell} refers to the capacity of the

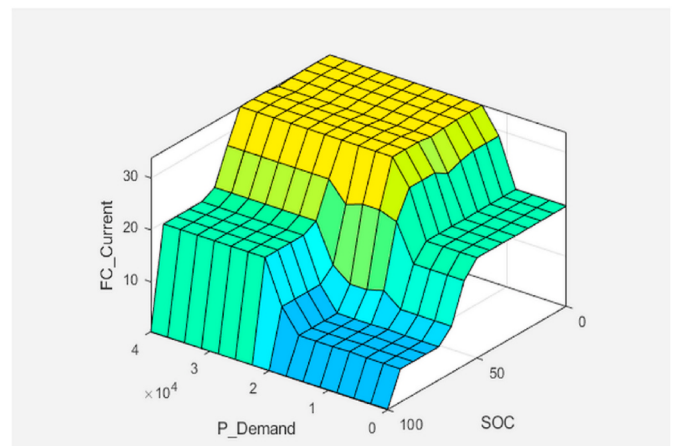


Fig. 9. Fuzzy surface showing the relationship between the output (FC current) and the inputs (Power demand and battery SOC).

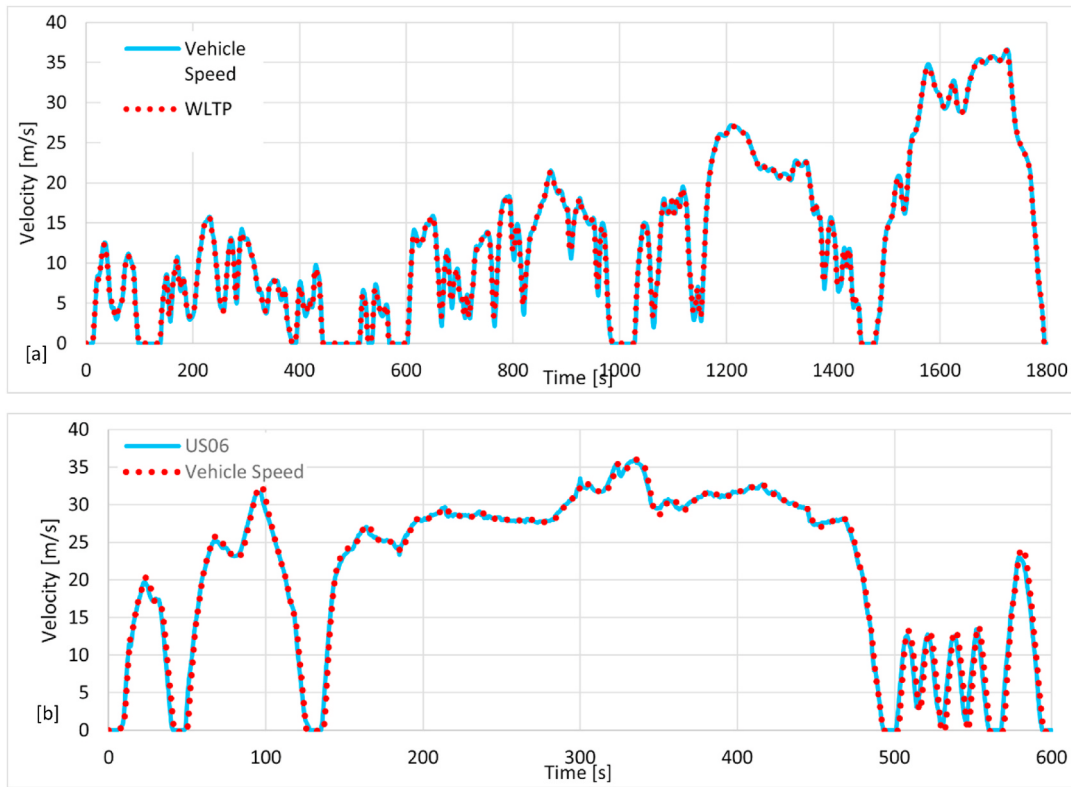


Fig. 10. The reference and the actual vehicle's speed profiles during the simulation cases a)WLTP b) US06.

cell/battery in ampere-hours (A), while $I_{Cell,dem}$ represents the current demand from the cell/battery in amperes (A).

$$SOC = SOC_0 - \left(\int_{t_0}^t \frac{I_{Cell,dem}(\tau)}{C_{Cell}} d\tau \right) \quad (15)$$

The battery pack model is built up by putting individual cells together. To calculate the power demand from a single cell, assuming identical cells in the pack, the total required power is scaled down by dividing it over the number of cells. After calculating the available power in a single cell, it is then scaled up using the same approach. Table 3 lists the specifications of the battery pack used in the SOFC vehicle model.

To model the driver, a speed-tracking PID controller is used based on previous studies in the literature (Hayes et al., 2011; Chen et al., 2013). The block diagram of the driver model is presented in Fig. 5. The PID controller works based on the error between the actual vehicle's velocity (V) and the reference velocity (i.e. a driving cycle). When the vehicle's velocity is lower than the reference value, an acceleration command is generated (gas pedal) whereas in the opposite case, a brake command is generated to reduce the velocity.

2.3. Energy management system (EMS) modelling

The vehicle concept, which is considered in this study, is a series hybrid fuel cell vehicle. The system configuration is illustrated in Fig. 6. In this concept, the fuel cell does not directly power the wheels but only charges the battery. The controller manages the distribution of current, directing it to the battery for storage and also using it to meet the vehicle's power demand. The vehicle component and driver determine the power demand, sending feedback to the controller to ensure the system meets the required performance under different conditions. A fuzzy logic controller is designed to perform the energy management task. In EMSs for SOFC battery hybrid vehicles, the choice of control strategy is

critical. While rule-based methods are simple and easy to implement, they often struggle to adapt to the dynamic and nonlinear nature of SOFC systems under rapidly changing conditions. Optimization-based approaches offer powerful solutions but are computationally intensive and require significant tuning to accommodate shifting scenarios. Fuzzy logic control provides an attractive balance between simplicity and adaptability, making it well-suited for handling uncertainties and nonlinearities in hybrid systems. The flexibility of fuzzy logic in handling linguistic variables allows it to manage the complex and dynamic behaviour of SOFC-battery hybrid vehicles effectively, ensuring both energy efficiency and system reliability (Zadeh, 1965; Hemi et al., 2014; Chen et al., 2018; Li et al., 2011).

The objectives of the EMS are to prevent excessive discharge and overcharge of the battery and to maintain the battery SOC around 60% (charge sustaining strategy) despite the fluctuations in the power demand and the SOFC is continuously operational during operation (Sahwal et al., 2024). The following part describes the structure of the fuzzy controller, including its inputs and outputs, membership functions, and rules and its block diagram.

The EMS model has two inputs: (i) power demand (P_demand), and (ii) battery SOC, as shown in Fig. 7. The power demand is assumed to have three levels called 'low', 'normal', and 'high', whereas the battery SOC is considered to have four levels called 'low', 'normal', 'high', and 'full'. The EMS model's output is the SOFC's current, which is used for battery charging. Four levels are considered for the output called 'zero', 'minimum', 'optimum', and 'maximum' charging. One membership function is used to model each level of the inputs and the output. Fig. 8 shows all the membership functions considered for the inputs and output of the proposed EMS fuzzy controller.

Table 4 displays the fuzzy rules, which are designed for the proposed EMS based on its input-output relationship. The objective of these rules is to maintain the battery SOC around 60% during the surveillance cycle and at the same time, to provide the required power. As an example of one rule, 'If the power demand is high and the battery SOC is high, the FC



Fig. 11. Battery SOC and FC current graphs during the WLTP simulation for different initial SOC: a) 80%, b) 65%, and c) 50%.

current is optimum'. Table 4 lists all the rules in one place.

In addition, Fig. 9 illustrates a fuzzy surface that visually shows the relationships between the EMS inputs (i.e. P_{demand} , and SOC), and its output (i.e. the FC current). The colour gradient on the surface represents the varying levels of current output, with cooler colours (blue/green) indicating lower current and warmer colours (yellow) representing higher current. As power demand increases, especially when SOC is low, the FC current rises to its maximum value, demonstrating the fuzzy controller's capacity to adapt and maintain energy balance efficiently.

3. Simulation results

This section includes a range of simulation results related to the SOFC alone as well as the whole vehicle. Looking at the whole vehicle model, a few simulation results are selected to be presented here. The driver model aims to follow reference velocity profiles, which are the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and the US06 driving cycles (EPA) (Vehicle Certification Agency, 2024). There are benefits of using two different driving cycles. The WLTP covers longer distances and includes urban, suburban, and motorway driving conditions. In contrast, the US06 driving cycle focuses more on

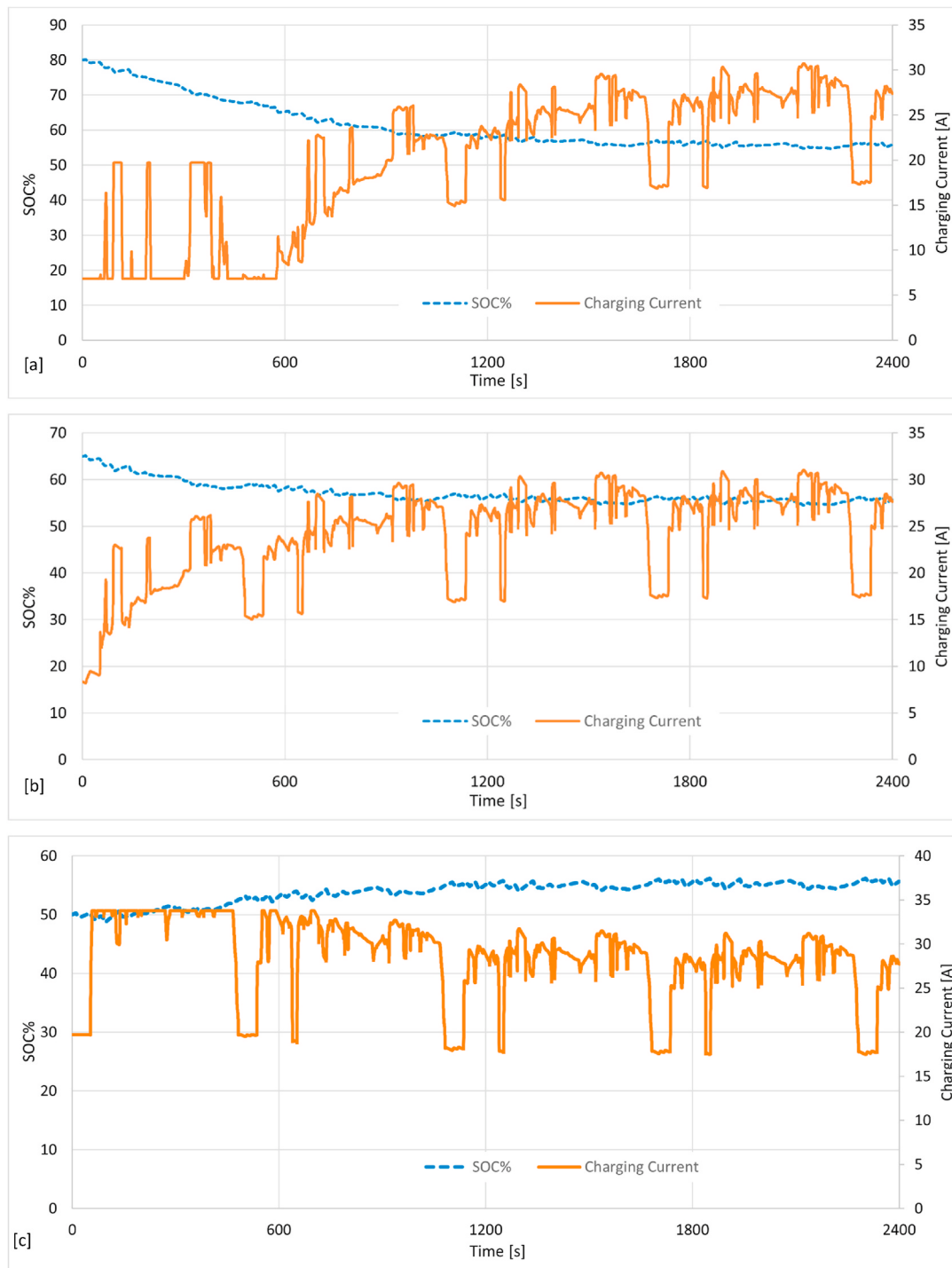


Fig. 12. Battery SOC and FC current graphs during the US06 simulation for different initial SOC: a) 80%, b) 65%, and c) 50%.

high-speed and high-acceleration situations. The driver model is responsible to keep the vehicle's speed within an allowable range (± 0.56 m/s) around the reference velocity by generating suitable acceleration and brake commands. Fig. 10 illustrates the reference speed and the actual vehicle's speed during the WLTP and US06 simulation case studies.

Figs. 11 and 12 contain three graphs illustrating the battery SOC and the SOFC's current during four consecutive WLTP and four US06 driving cycles. The purpose of applying four consecutive driving cycles is to check the battery charge sustaining. In both WLTP and US06 cases, the initial SOC of the battery is changed by starting at 50%, 65% and 80%.

The goal is to keep the battery SOC around 60% all the time. In fact, the three cases are designed to evaluate the EMS performance by starting at a lower SOC (i.e. 50%), around the target SOC (i.e. 65%), and a higher SOC (i.e. 80%). According to the results of all six cases, the battery SOC is successfully stabilized around 60% during the simulations regardless of the initial charge level. The orange lines in the graph are crucial to understand the performance of the EMS. As explained in the energy management system modelling section, there is a dynamic charge management system based on the battery state and the power demand of the vehicle (shown in Fig. 13). The fluctuation of the orange lines indicates that the charging current decreases when the vehicle consumes

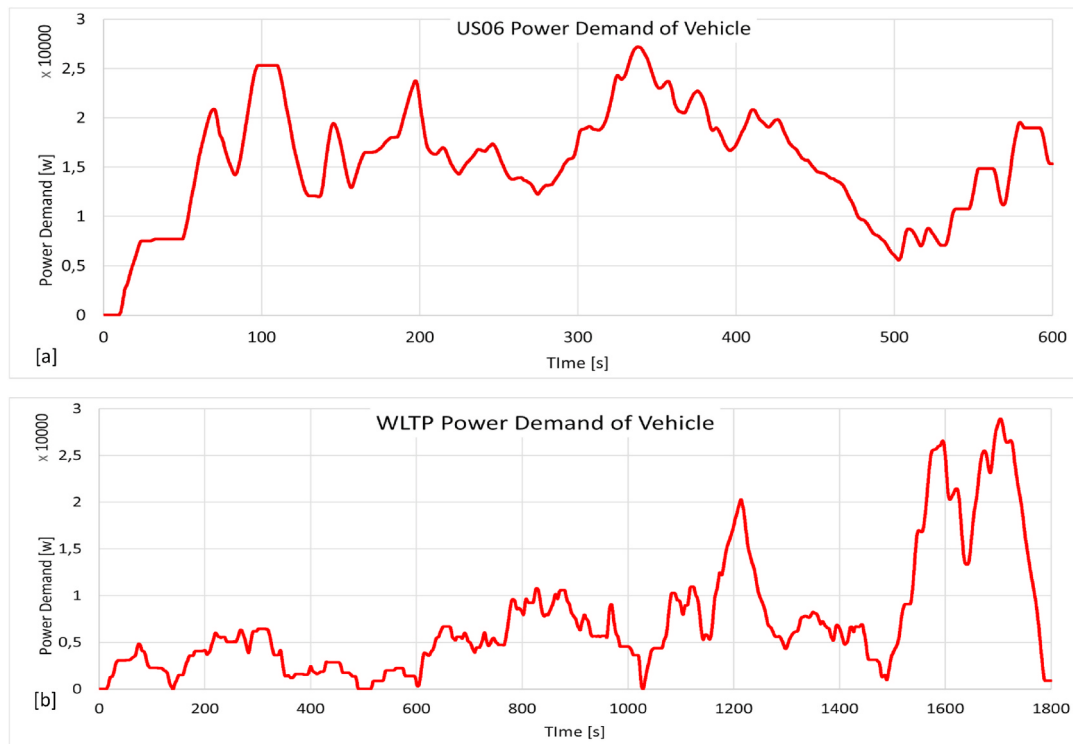


Fig. 13. Vehicle power demand over driving cycles a)US06 b)WLTP.

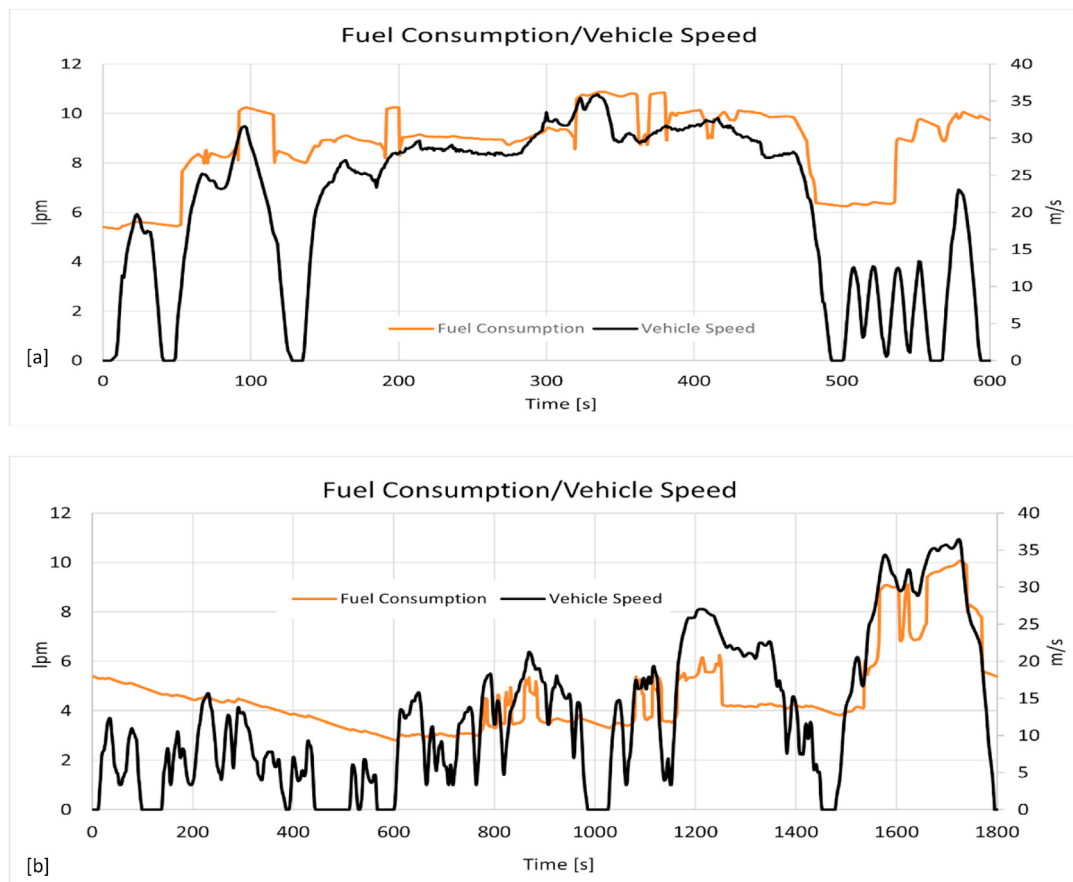


Fig. 14. Vehicle fuel consumption simulation over driving cycles a) US06 b) WLTP.

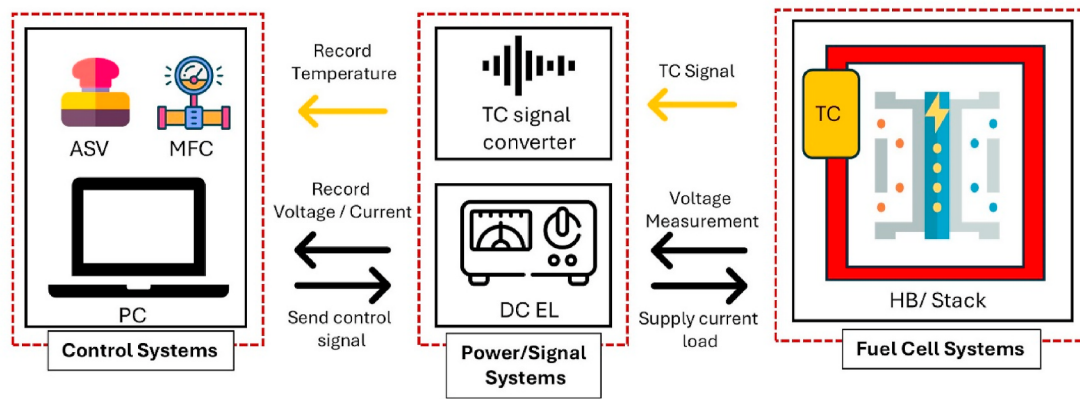


Fig. 15. Schematic of the experimental setup for SOFC testing.

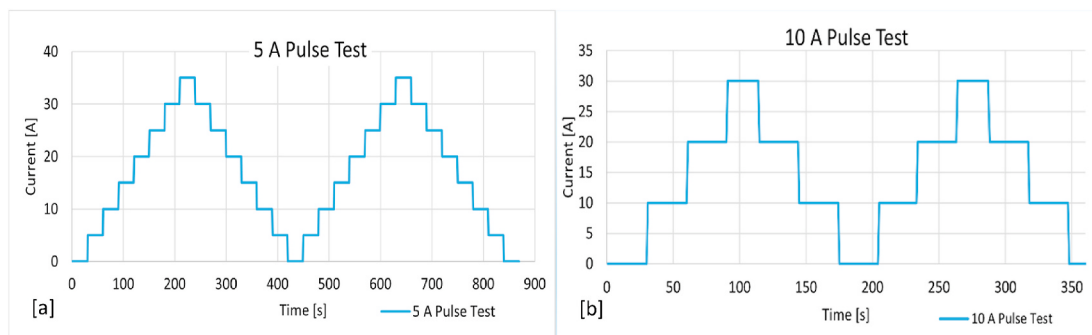


Fig. 16. Current pulse tests designed for experimental validation of SOFC: (a) 5A pulses, (b) 10A pulses.

less energy or the battery charge is high, and it increases in the opposite case. The controller's objective is to preserve the battery's health by preventing over-charging or over-discharging and maintaining the charge level around 60%. In conclusion, the graphs demonstrate that the proposed EMS effectively manages the SOFC's current according to the power demand and the battery SOC.

Fig. 14 shows the fuel consumption of the SOFC vehicle during the WLTP and US06 simulation cases when the initial SOC is 60%. In the first graph, during the WLTP driving cycle, the vehicle speed generally shows lower average and more fluctuations, whereas the fuel consumption remains relatively constant during the US06 simulation but at a higher level due to the more aggressive driving conditions.

4. Validation of the SOFC performance based on experimental tests

As a complementary analysis in this study, a 700-W SOFC stack (SOFCMAN Ningbo, China) consisting of 30 planar anode-supported cells, is experimentally tested. The stack had a Ni-YSZ/YSZ/CGO/LSCF-CGO configuration, with a cell size of 14×14 cm and an expected active area of 150 cm^2 . The stack was placed in a 3.5 kW furnace (SOFCMAN Ningbo, China) and heated to 750°C . Before any stack reduction, the anode side of the stack was purged with 4 L min^{-1} of nitrogen for 10 min. Fig. 15 presents a schematic diagram of the experimental setup used in this study. The setup includes three main parts: the control system, the power/signal system, and the fuel cell system. The control system includes the automatic shut-off valve (ASV) and the mass flow controller (MFC) to regulate the flow of hydrogen,

oxygen, and nitrogen. These components are managed via a PC, which sends control signals and records essential parameters such as voltage and current. The power/signal system is responsible for voltage measurements and supplying current load through a direct current electronic load (DC EL). Temperature signals from the thermocouples (TC) are converted and transmitted for monitoring through the TC signal converter. The thermocouples, located within the fuel cell system, play a critical role in monitoring and managing the temperature inside the hot box (HB) and the fuel cell stack for performance evaluation and safety. The reduction of the stack was initiated by introducing 4 L min^{-1} of hydrogen and 12 L min^{-1} of air into the anode and cathode sides, respectively. Both the hydrogen and air streams were preheated to 600°C and 500°C before being fed into the stack. The average cell open circuit potential (OCP) is 1.10 V per cell.

It was observed in the simulation results that high current demands can be placed on the SOFC in situations where high power is required, such as in the EV application. In this section, pulse tests are designed to measure how quickly and effectively the SOFC responds to rapid and short-term load increases as shown in Fig. 16. These tests consist of a series of charging current periods in 5A and 10A increments, with current demands up to a maximum of 35A. The maximum 35A is decided based on the simulation results that showed a maximum battery charging current of 35A.

The response time of the SOFC and the actual current values against the set current values are recorded during the tests as depicted in Fig. 17. According to the test results, the SOFC stack demonstrates excellent performance in load change scenarios with very short response time. As shown in the figure, the SOFC consistently delivers the demanded

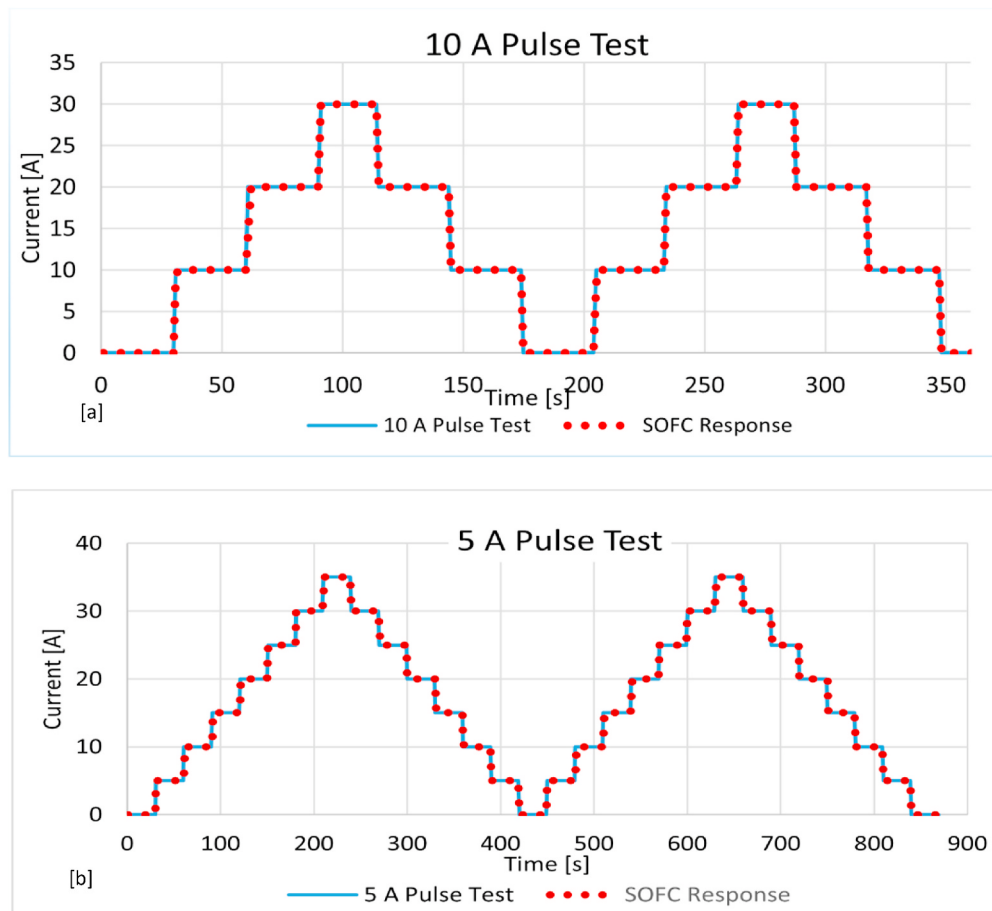


Fig. 17. Comparison between the SOFC response and the reference current demand: (a) 10A pulses, (b) 5A pulses.

current with an error rate of less than 0.1%. Additionally, during these tests, it was observed that the temperature of the SOFC remained approximately 750 °C which ± 0.5 °C.

Furthermore, to validate the simulation model against experimental results, a comparison between the SOFC response and the simulation voltage is conducted as illustrated in Fig. 18. The figure depicts the voltage response of the SOFC under 5A and 10A pulse conditions. The results indicate a close match between the simulation model and the experimental voltage data.

5. Conclusions

This study examined the potential use of a SOFC stack in the automotive sector for vehicle propulsion system. The potential impact of this study is connected to the advantages of the SOFC technology such as its high energy efficiency, compatibility with various fuels, and environmentally friendly qualities, which make it an attractive option for clean vehicle propulsion. A 6 kW SOFC stack was modelled and validated based on literature. The SOFC model was then incorporated into a series hybrid electric vehicle model to simulate its performance in such an application. The vehicle's actual speed under these conditions had a maximum error of only ± 0.56 m/s compared to the reference speed. A fuzzy rule-based EMS controller was then designed and implemented into the vehicle model. According to the results, the proposed controller could effectively manage the charging current between the battery and

the SOFC to ensure optimum performance under varying load conditions. The controller could successfully maintain the battery charge level around 60% to prevent battery over-charging and over-discharging. Finally, experimental tests were designed and conducted to make sure a real SOFC stack can deal with the quick changes in power demand, which are expected in automotive application. The tests designed for this purpose provide valuable information on the performance of a SOFC under dynamic loads. In the repeated and variable step pulse tests, the SOFC showed a very good performance against the required current and voltage values.

While the SOFC system shows great potential, its startup time remains a notable limitation, particularly for applications requiring rapid deployment. Although significant advancements have been made in improving cold start performance, these technologies are not yet commercially available (Wang et al., 2024; Jeong et al., 2023). In the present study, experiments were conducted at the optimal operating temperatures, and cold start performance was not evaluated. However, this limitation is less relevant for long-running vehicles where the system remains operational for extended periods, reducing the impact of startup delay. Additionally, the SOFC system supports cleaner and more sustainable vehicle propulsion by optimizing energy use and reducing emissions. Its ability to use alternative fuels such as ethanol and ammonia adds to its environmental benefits, making it a promising solution even in regions lacking hydrogen infrastructure.

In conclusion, this study bridges the gap between theoretical

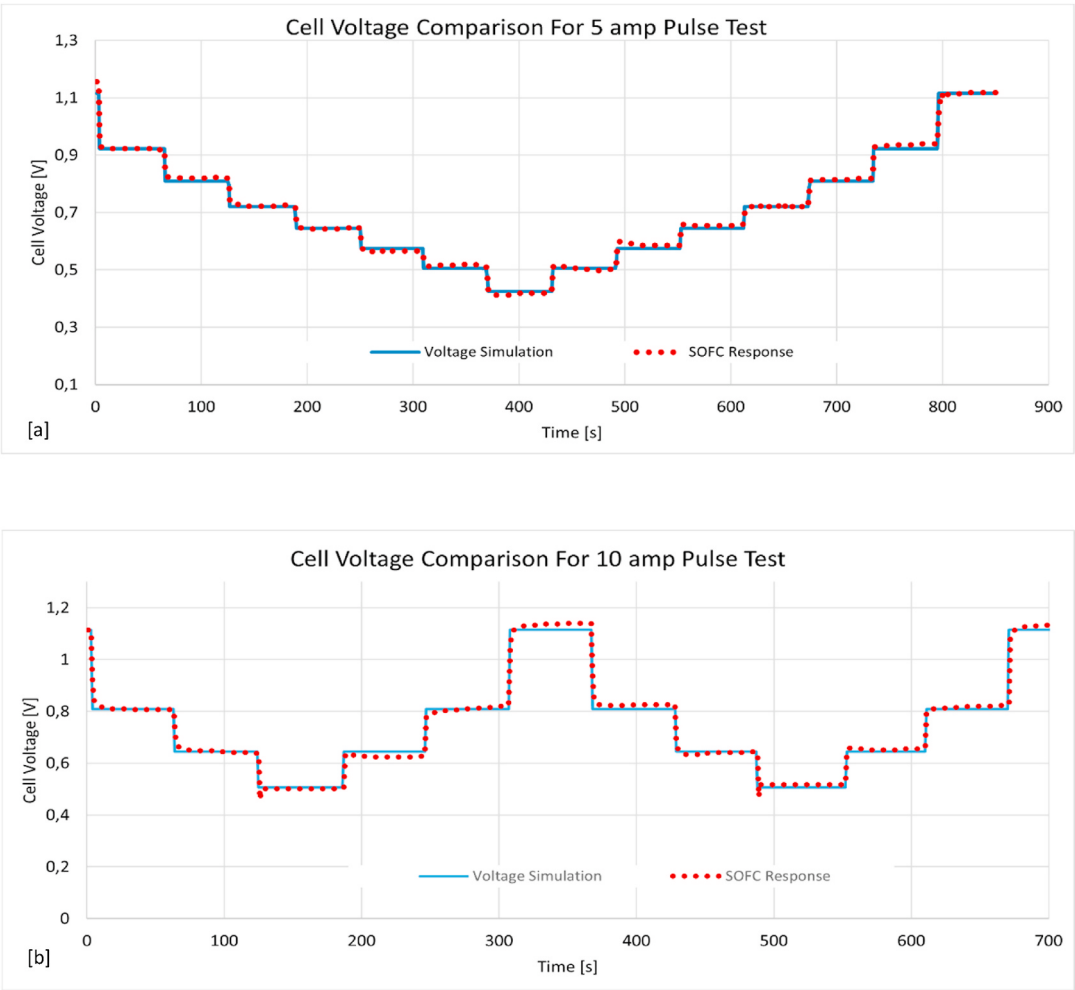


Fig. 18. Comparison between the SOFC response and the simulation voltage: (a) 5A pulses, (b) 10A pulses.

simulation and practical application by demonstrating the successful integration of an SOFC stack into a hybrid vehicle model and validating its performance through both simulation and experimental testing. Research on the wider applicability of SOFCs and their use in commercial vehicles is expected to increase as more work is done to shorten start-up time and improve cold start performance.

CRediT authorship contribution statement

Ibrahim Kasar: Writing – original draft, Validation, Methodology, Conceptualization. **Abbas Fotouhi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Seyed Ali Nabavi:** Writing – review & editing, Supervision, Conceptualization.

Appendix A

Table 5
SOFC modelling equations.

Parameter	Formula	Description
Nernst Voltage (<i>Enerst</i>) (Ni et al., 2007)	$Enerst = E_0 + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}}$	Reversible cell voltage and its variations as a function of gas compositions.
Standard Reversible Cell Voltage (<i>E₀</i>) (Ni et al., 2007)	$E_0 = 1.2353 - 2.4516 \cdot 10^{-4} \cdot T$	Ideal or reversible voltage based on Gibbs free energy change.

(continued on next page)

Table 5 (continued)

	Parameter	Formula	Description
Ohmic Voltage	Ohmic Voltages (V_{ohm}) (Yahya et al., 2018)	$V_{ohm} = I \cdot ASR$	Voltage loss due to resistance in the electrolyte and electrodes.
	Area Specific Resistance (ASR) (Yahya et al., 2018)	$ASR = \frac{L_e}{\sigma_{el}} + R_{ct}$	Resistance per unit area of the cell.
	Electrolyte Ionic Conductivity (σ_{el}) (Yahya et al., 2018)	$\sigma_{el} = \frac{\sigma_{0,el}}{T} \exp\left(\frac{-E_{act,el}}{RT}\right)$	The conductivity of the electrolyte as a function of temperature.
Activation Voltage	Activation Voltages ($V_{act,an,cat}$) (Ni et al., 2007)	$V_{act,an,cat} = \frac{2RT}{nF} \ln\left(\frac{i}{2i_0} + \sqrt{1 + \left(\frac{i}{2i_0}\right)^2}\right)$	Voltage loss due to the activation energy required for electrochemical reactions.
	Exchange Current Density ($i_{0,an}$) (Ren et al., 2012)	$i_{0,an} = \gamma_{an} \left(\frac{p_{H_2}}{p}\right) \left(\frac{p_{H_2O}}{p}\right) e^{\left(\frac{-E_{act,an}}{RT}\right)}$	Current density for the anode.
	Exchange Current Density ($i_{0,ca}$) (Ren et al., 2012)	$i_{0,ca} = \gamma_{ca} \left(\frac{p_{O_2}}{p}\right)^{0.25} e^{\left(\frac{-E_{act,ca}}{RT}\right)}$	Current density for the cathode.
Concentration Voltage	Concentration Voltage ($V_{conc,an}$; $V_{conc,cat}$) (Yahya et al., 2018)	$V_{conc,an} = -\frac{RT}{nF} \ln\left(\frac{1 - \frac{i}{i_{L,H_2}}}{1 + \frac{i}{i_{L,H_2O}}}\right)$ $V_{conc,cat} = -\frac{RT}{nF} \ln\left(1 - \frac{i}{i_{L,O_2}}\right)$	Voltage loss due to changes in reactant concentrations at the electrode surfaces (anode).
	Limiting Current Density for Hydrogen (i_{L,H_2}) (Yahya et al., 2018)	$i_{L,H_2} = \frac{nFD_{H_2}^{eff}}{RT} p_{H_2}$	The limiting current density for hydrogen, using the effective diffusion coefficient and partial pressure of hydrogen.
	Limiting Current Density for Water (i_{L,H_2O}) (Yahya et al., 2018)	$i_{L,H_2O} = \frac{nFD_{H_2O}^{eff}}{RT} p_{H_2O}$	The limiting current density for water, using the effective diffusion coefficient and partial pressure of water
	Limiting Current Density for Oxygen (i_{L,O_2}) (Yahya et al., 2018)	$i_{L,O_2} = \frac{nFD_{O_2}^{eff}}{RTc_c \left(1 - \frac{p_{O_2} \cdot \delta_{O_2}}{p}\right)} p_{O_2}$	The limiting current density for oxygen, using the effective diffusion coefficient and partial pressure of oxygen.
	Effective Diffusion Coefficient (D_A^{eff}) (Yahya et al., 2018)	$D_A^{eff} = D_A \frac{\epsilon_{anode \text{ or cathode}}}{\tau_{anode \text{ or cathode}}}$	The effective diffusion coefficient of a species, considering the porosity and tortuosity of the anode or cathode.
	Diffusion Coefficient Ratio (δ_{O_2}) (Ni et al., 2007)	$\delta_{O_2} = \frac{D_{O_2,Knudsen}^{eff}}{D_{O_2,Knudsen}^{eff} + D_{O_2,N_2}^{eff}}$	the diffusion ratio for oxygen, considering Knudsen diffusion and effective diffusion coefficients.
	Mixture Molar Mass (M_{AB}) (Yahya et al., 2018)	$M_{AB} = 2 \left(\frac{1}{M_A} + \frac{1}{M_B}\right)^{-1}$	the molar mass of a gas mixture
	Diffusion Coefficient (Yahya et al., 2018)	$D_{AB} = \frac{0.00143 \cdot T^{1.75}}{p \sqrt{M_{AB}} \left(V_A^{1/3} + V_B^{1/3}\right)^2}$	The binary diffusion coefficient, considering temperature, pressure, and molar volumes of the gases.
	Overall Diffusion Coefficient (Yahya et al., 2018)	$\frac{1}{D_A} = \left(\frac{1}{D_{AB}} + \frac{1}{D_{A,Knudsen}}\right)$	The overall diffusion coefficient, considering both bulk and Knudsen diffusion coefficients.
	Knudsen Diffusion Coefficient (Yahya et al., 2018)	$D_{A,Knudsen} = 97 \cdot r_{por} \sqrt{\frac{T}{M_A}}$	The Knudsen diffusion coefficient, considering pore radius, temperature, and molar mass of the species.

Data availability

The data presented in this study will be available on request from the corresponding author and from CORD at <https://doi.org/10.57996/cran.ceres-2668> after an embargo period.<https://doi.org/10.17862/cranfield.rd.25710093>

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2025-01-01

Elsevier

<https://doi.org/10.1016/j.jclepro.2024.144422>

Kasar I, Fotouhi A, Nabavi SA. (2025) Performance test of a hydrogen-powered solid oxide fuel cell system and its simulation for vehicle propulsion application. Journal of Cleaner Production, Volume 486, January 2025, Article number 144422