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Impact of Oxygen Concentration on High-Load PEMFC Efficiency: A Simulink-Based Study

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Abstract: Energy consumption and the utilization of sustainable energy sources are of great importance for the economic independence and environmental stability of nations. Turkey, as a country heavily dependent on energy imports, faces a critical need to develop domestic and renewable energy resources. The low carbon emissions and environmentally friendly nature of hydrogen have attracted significant attention within the scope of international agreements such as the Kyoto Protocol. Proton Exchange Membrane Fuel Cells (PEMFCs) stand out among clean energy technologies due to their low operating temperatures (60–80°C), high power density, and zero-emission potential. However, concentration losses occurring on the cathode side under high load conditions represent a significant problem that considerably reduces PEMFC efficiency and has not been sufficiently addressed in the literature.

This study investigates the effect of inlet air O_2 on PEMFC efficiency under different load conditions using a MATLAB-Simulink simulation model. The results demonstrate that increasing the oxygen concentration under 50% load conditions yields only a marginal efficiency improvement of approximately 3%. In contrast, under 90% load conditions, increasing the O_2 enrichment level from 21% to 100% improves efficiency by approximately 10%, and this gain can reach up to 15% with additional pressurization measures. This finding clearly demonstrates that increasing oxygen concentration provides a meaningful contribution only under high load conditions, while such intervention is unnecessary within the optimal load range. The results present a practical strategy for improving PEMFC efficiency in heavy-load applications such as intercontinental cargo ships and freight trains, and directly contribute to the literature on PEMFC systems operating under high load conditions.

Keywords Concentration loss, Energy efficiency, High-load operation, MATLAB/Simulink, Oxygen enrichment, PEMFC

1. Introduction

Energy, in whatever form, is one of the fundamental elements that living beings need and that affects all our relationships (Erkök & Kütük, 2023). In today's world, where technology is rapidly developing and demand is increasing, carbon emissions have also resonated and have been accepted on the world agenda

with the Kyoto Protocol. The fact that it is cost-effective, sustainable, and readily available to users forms the basis of renewable energy. Turkey is a country largely dependent on imported energy to meet its energy needs, and this high external dependence constitutes a significant obstacle to our country's independence. The continuous increase in energy needs and the desire to reduce the use of fossil fuels or to diversify needs with different energy sources, along with new perspectives such as clean energy, are increasing interest in hydrogen energy day by day. Therefore, hydrogen energy is attracting the attention of many researchers.
Hydrogen is one of the most promising alternative sources for reducing our country's energy dependence. Hydrogen is known by different names depending on its production methods. The most common method of hydrogen production is electrolysis, as shown in Figure 1. Electrolysis is the process of separating water into hydrogen and oxygen by supplying energy to the anode and cathode. When the energy required for the electrolysis process is obtained from renewable sources such as solar and wind energy, the energy produced from this electrolysis is called green hydrogen (Dincer & Acar, 2015); if fossil fuels are used, it is called gray hydrogen; if the carbon dioxide gas released during its production from fossil fuels is prevented from being released into the atmosphere by using carbon capture and storage technology at the power plant, it is called blue hydrogen; and if the energy is supplied from the grid or nuclear energy, it is called yellow hydrogen (Incer-Valverde et al., 2023).

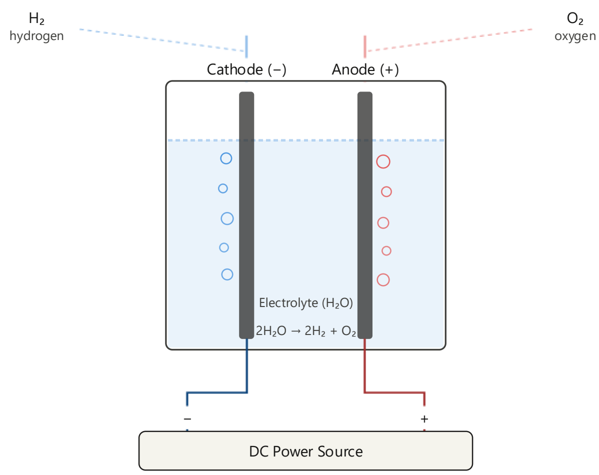

Figure 1 Principle of Water Electrolysis

Hydrogen energy's contribution to low carbon emissions makes it a focus of global attention, and it is also considered an environmentally friendly technology because it provides energy production without carbon emissions. Due to these characteristics, it attracts the interest of many users both as a clean and efficient energy source in energy production and as a contribution to areas such as transportation with fuel cells. Hybrid vehicles offer an environmentally friendly transportation alternative that operates with a combination of electric and hydrogen energy. A significant part of the research on the use of hydrogen as an energy source has been conducted on proton exchange membrane fuel cells (PEMFCs), which have zero emission potential, do not emit high heat during operation, and are considered one of the clean energy sources (Y. Wang et al., 2011). Research has been conducted to optimize the efficiency of these fuel cells by studying membrane water management, catalyst stability, oxygen partial pressure, and concentration losses (Weber & Newman, 2004).
Fuel cells are electrochemical machines that convert chemical energy directly into electrical energy, based on the basic principle of an internal combustion engine. Hydrogen is typically used as the fuel, and oxygen as the oxidizer. This process takes place at the anode, where the fuel is separated into protons and electrons; protons are transported to the cathode via the electrolyte, and electrons create an electric current in the

external circuit. At the end of the reaction, the protons combine with oxygen at the cathode to produce water, leaving only water as a byproduct. Hydrogen energy also presents some technical challenges. Difficulties such as the storage, compression, and liquefaction of hydrogen should not be overlooked (Sherif et al., 2005). PEMFCs are modeled, particularly in the environment provided by Matlab Simulink, to determine the different behaviors of the fuel cell. Ansari et al. modeled the Horizon H-500 fuel cell in the Matlab Simulink environment and conducted studies on its thermodynamic and steady-state behaviors (Ansari et al., 2021). The study revealed that the inlet gas pressure and ambient temperature are important variables affecting the performance of the PEMFC. Zhou et al. conducted studies on how different oxygen concentrations affect the performance and durability of PEMFCs (Zhou et al., 2026). The studies presented here demonstrate that O_2 enrichment level is important under high load conditions. Beni Hamed & Ben Hamed investigated the electrical characteristics of PEMFC stacks under different operating conditions, such as oxygen pressure, membrane water content, temperature, and hydrogen pressure (Beni Hamed & Ben Hamed, 2024). Their study suggests that membrane water content and inlet gas pressure significantly influence the outcome. Therefore, they argue that optimizing these factors to achieve efficient fuel cells is more meaningful. As the studies presented here demonstrate, the efficiency of PEMFCs can vary depending on different conditions.

This study attempts to demonstrate that PEMFCs can operate more efficiently under high load conditions by applying a higher O_2 enrichment level to the cell inlet. Increasing the efficiency of fuel cells under high load conditions provides a significant advantage, especially by reducing the weight and volume of the system. This study presents a different perspective on increasing the efficiency of long-haul transportation vehicles (such as cargo ships, freight trains, and trucks) with high power requirements. The simulation studies conducted also confirm the propositions presented here.

2. PEMFC Fuel Cell and Its Basic Components

Since PEM (Proton Exchange Membrane) is a current and important topic, studies on this subject can be found on many platforms. In Simulink, a simulation program used in MATLAB, a hydrogen fuel cell block based on the Nernst equation has been designed as a result of studies on hydrogen. Using the blocks discussed in detail below, a realistic hydrogen fuel cell has been designed in the simulation program, and studies have been conducted to determine ideal operating conditions. The basic elements of the fuel cell are shown in Figure 2.

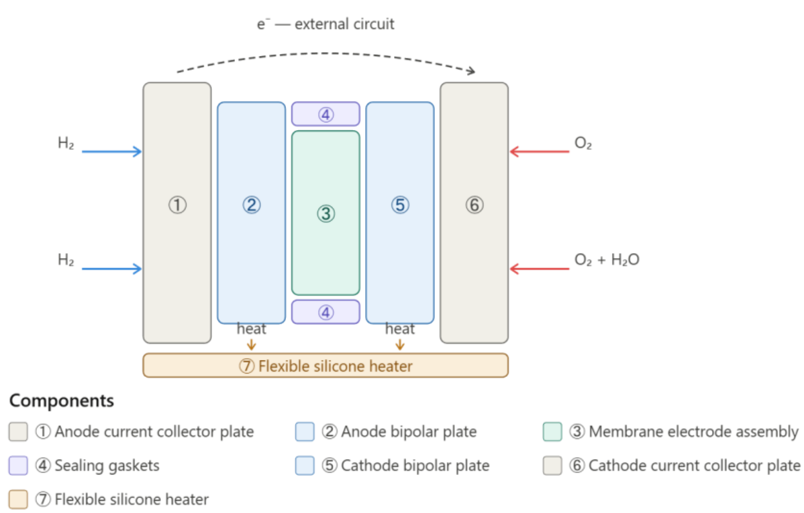

Figure 2 Layered structure of a PEMFC stack and its basic components.

2.1 Simulation Working Conditions

To obtain the most accurate result for the output voltage that the fuel cell will provide in the simulation, it is necessary to define the operating conditions in the simulation as closely as possible to reality. The Simulink environment creates the different operating environments required in PEMFC systems and helps us to have a realistic simulation (Ansari et al., 2021). Therefore, MATLAB-Simulink-based modeling approaches were preferred in this study.

2.2 Nernst Equation

In electrochemistry, the Nernst equation is an equation that relates the electrode potential of an electrochemical cell to the standard electrode potential, temperature, and the activities of the reactants (usually approximated by concentrations). This equation allows us to predict the behavior of the cell under conditions different from standard conditions. Because of this feature, the Nernst equation plays a very important role in PEMFC modeling (Mench, 2008).
The Nernst equation, which forms the basis of the model, is expressed as follows (Equation 1):

$$E = E^0 - \frac{RT}{nF} ln \frac{[products]}{[reactants]} \tag{1}$$

where, E represents the electrode potential of the cell, and E^0 symbolizes the electrode potential under standard conditions. T symbolizes the absolute temperature (Kelvin), n the number of reacting electrons, R the universal gas constant (8.314 J/mol·K), and F the Faraday constant (96,485 C/mol). In PEMFCs, this equation is customized to use the partial pressures of hydrogen and oxygen along with the operating temperature, as shown in the equation below (Equation 2):

$$E = E^0 - \frac{RT}{nF} \ln \left(P_{H_2} . P_{O_2}^{1/2} \right) \tag{2}$$

where, P_{H_2} represents the partial pressure of hydrogen, while P_{O_2} represents the partial pressure of oxygen. When the equation above is examined, it is seen that increasing the partial pressures of oxygen and hydrogen directly contributes to raising the potential in the cell. Meanwhile, moisture losses that may occur in the membrane also affect the decrease in the total cell voltage. Therefore, ambient temperature is also related to cell voltage (Weber & Newman, 2004). In this study, the simulation model developed in the MATLAB-Simulink environment is based on this equation.

2.3 Concentration Loss

Concentration or mass transfer losses result from variations in the density of gases present on the anode and cathode electrode surfaces (Mann et al., 2000).The research area of this article largely focuses on reducing concentration losses. Since concentration losses are related to high load operations, these losses have been ignored in several key hydrogen fuel cell studies. For instance, (Ansari et al., 2021) focused on thermodynamic and steady-state behaviors without addressing concentration losses at high loads. Similarly, the term mass transfer is also not used in NASA studies because sufficiently high current densities are not studied to obtain information about mass transfer limitations (Smith et al., 2021). Weber and Newman (2004), while providing comprehensive transport modeling, primarily focused on membrane water management rather than high-load concentration effects.
In PEMs, concentration losses are related to the inlet air concentration. The oxygen content in the air is 21%. When the load reaches 90%, increasing the pressure on the cathode side to fully affect the cathode surface area of the PEM by supplying 100% oxygen from the air inlet reduces the concentration loss. Feeding the air inlet of the fuel cell with pure oxygen is possible with oxygen cylinders or tanks. A standard oxygen cylinder is stored in tanks that can withstand pressures up to 8 bar. Examples of potential hazards to a system containing an oxygen tank include fire risk, the flammability of hydrogen and its easier reaction with pure

oxygen, and cost considerations. According to Zhang et al., if oxygen-enriched air, which has similar limitations to pure oxygen, is disregarded, compressing the inlet air to higher pressures is probably the most suitable solution; however, this requires a larger air compressor and negatively impacts the overall system size and cost (Zhang et al., 2013). Xia also conducted a pressure-dependent performance evaluation in a PEMFC simulation study. The results showed that oxygen pressure has a more significant effect on output voltage than hydrogen pressure (Xia et al., 2023).

The long-term effects of O_2 enrichment level used within the system are also not yet known. The most sensitive component within a PEM is undoubtedly the membrane. Dryness in the membranes, depending on the ambient conditions, negatively affects the reaction and consequently proton conductivity (Baz et al., 2024). Therefore, water supply is of great importance for PEMs. In addition, the effects of long-term use of the membrane are still not fully understood. According to Wang et al., the decreases in platinum metal concentration after long-term operation may be due to the dissolution of Pt and the formation of PtO and PtO_2 at the anode and cathode (Z. B. Wang et al., 2009).

2.4 Matlab Simulink PEM Simulation and Component Description

The basic components of a hydrogen fuel cell created in Matlab Simulink are shown in the Figure 3 below. The PEM inputs and outputs, provided as ready-made templates in the Simulink program, must be manually configured by the user. Using the Nernst equation, the user creates a system for the inputs and outputs of this fuel cell, varying according to the intended use. The PEM system consists of two inputs: the fuel input is the section where hydrogen is supplied; the other is configured to accommodate the O_2 enrichment level variable.

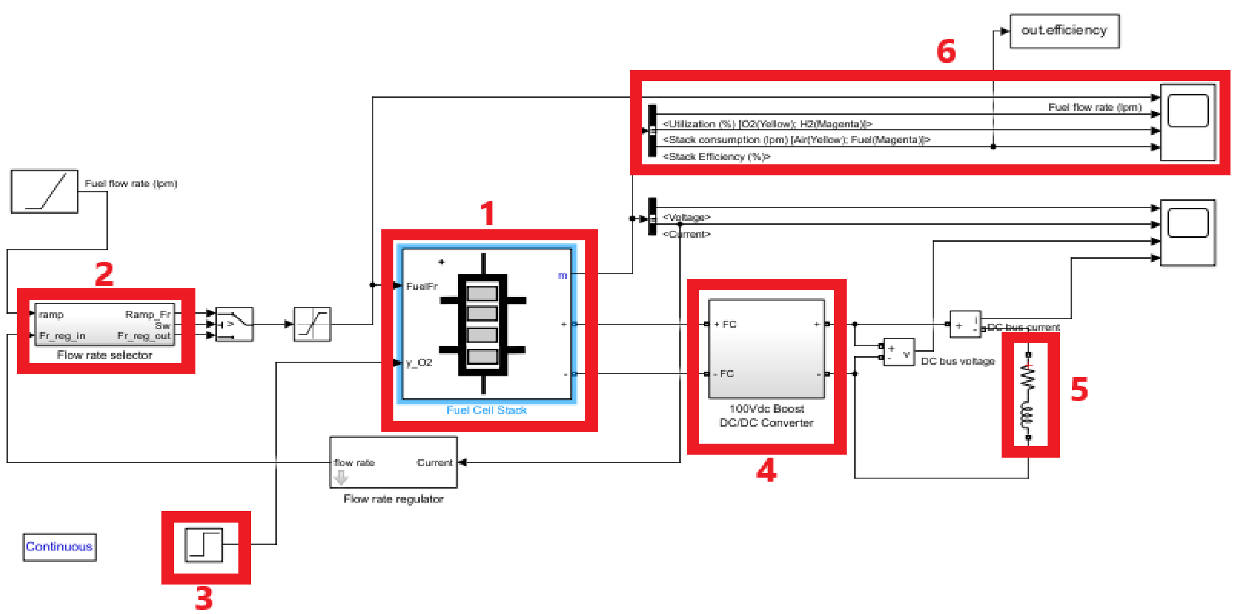

Figure 3 Fuel Cell PEM Simulation and Components

The simulation model consists of seven main components, each performing a different function. The component designated as number 1 is the Fuel Cell stack, the main part of the PEM where fuel and oxygen enter, all reactions take place, and electrical energy is generated. Number 2 shows the Flow Rate Selector, which adjusts and controls the fuel flow rate into the system; this block determines the rate at which fuel enters the cell. Number 3 represents the Signal Source, which applies a sinusoidal signal to the model to test the system's operating conditions, examine its response behavior, and generate variable input. Number

4 shows the DC/DC Boost Converter, which takes the variable DC voltage from the PEM and increases it to a high and stable level. Number 5 shows the LOAD, where the generated and converted electricity is consumed; this load consists of resistor and inductor elements representing a real electrical consumer. Number 6 indicates the Scope screen, where critical data such as current, voltage, efficiency, and flow rate generated during the simulation are graphically monitored; this section is not present in practice but is a necessary circuit element for reading the values in the simulation. Finally, the section indicated by number 7 is where the input values of the fuel cell are determined. Oxygen concentration, which is the subject of this study, has been chosen as the basic input variable.

3. Simulation-Based Analysis

Recognizing real-world conditions in PEMFC systems and verifying these through modeling studies is crucial for identifying and understanding the system's limitations. This section presents simulation-based studies on temperature, humidity, pressure, and load conditions affecting PEMFC efficiency.

According to the work of Rohendi et al., operating a PEM for 100 hours under ideal conditions reduces its efficiency by 20%. A PEMFC operating at 80°C for 100 hours showed a significant performance degradation with an open-circuit voltage (OCV) drop of approximately 20% (<15% OCV drop) compared to measurements obtained from ambient temperature operations (Rohendi et al., 2015). The results obtained here demonstrate that membrane degradation occurs in PEMFCs when operated for extended periods, and they cannot exhibit stable performance.

Figure 4 shows the temperature-efficiency graph. As can be seen from this graph, the efficiency of a fuel cell operating in the 50-80°C range does not remain constant with temperature. As the temperature increases between 50-65°C, efficiency also increases, but a dip occurs at 65°C. This dip is related to the membrane's difficulty in controlling moisture at this point. When the optimum region is reached, efficiency increases again; therefore, the most efficient operating temperature range for this fuel cell can be given as 65-80°C in the label values. In their study, Weber and Newman mathematically addressed the fact that efficiency decreases when the membrane moisture level goes outside the defined limits (Weber & Newman, 2004).

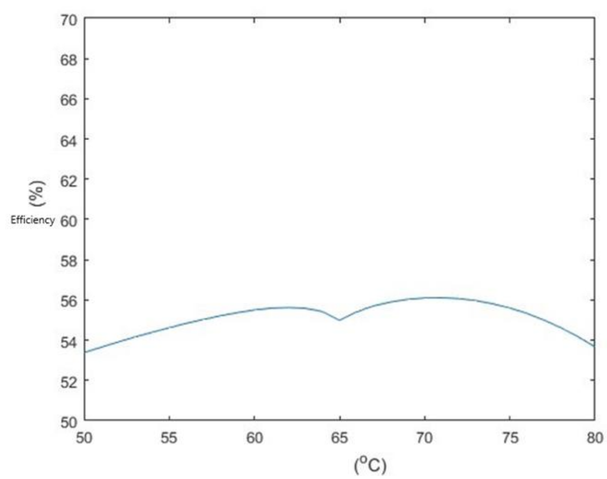

Figure 4 Effect of Temperature on Efficiency at Optimum Load (60-75%)

Here, operating the cell above the determined optimum load will produce more water, preventing it from reaching the evaporation temperature (Figure 5). Because the water cannot be drained, the pores will fill with water, and the gases will not reach the catalyst. This will lead to reduced efficiency. Similarly, at low loads and high temperatures, water production will decrease, the humidity will drop, and the environment will not be suitable for sufficient production. To achieve this internal balance, Weber et al. investigated how water management under optimum operating conditions affects gas emissions; they proved that the Nafion membrane is not merely a plastic technology, but a nanometer-scale structure that manages dynamics such as drying and gas diffusion limitation according to specific conditions (Kusoglu & Weber, 2017).

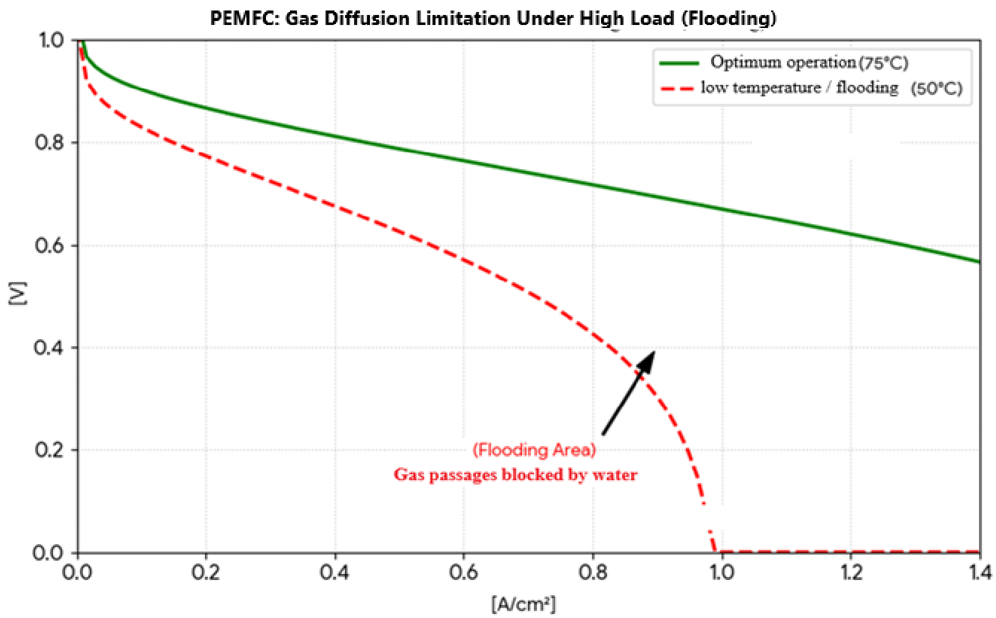

Figure 5 Flooding at 90% load and low temperature.

As shown in Figure 6, the cell exhibits the most efficient operation when oxygen and hydrogen are applied at equal pressures; however, this modeling reveals that voltage is more sensitive to oxygen pressure than hydrogen pressure. Simulation results showed that the applied pressure can have a negative effect on the membrane, with oxygen pressure having a more positive effect than hydrogen pressure.

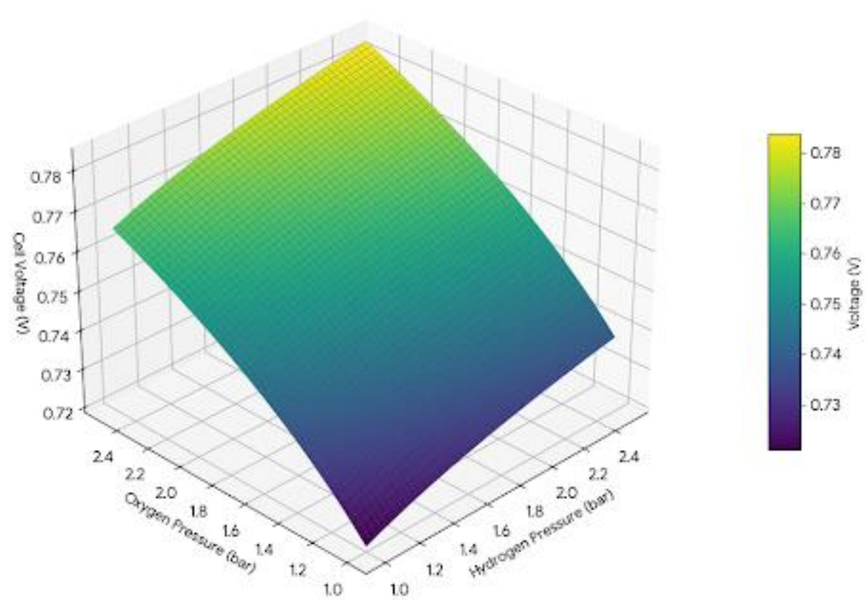

Figure 6 Effect of oxygen and hydrogen pressure balance on output voltage

For PEMFCs, 70-90% humidity has been identified as the optimum level for achieving optimal proton conductivity efficiency. At 20% membrane humidity, proton conductivity is very low because a dry membrane has high resistance, leading to low proton conductivity and consequently voltage drop. Operating the membrane within the optimum humidity band maximizes proton conductivity and increases voltage to high levels. When humidity reaches 100% or above, oxygen and hydrogen gases cannot reach the catalyst due to high water density, and voltage drops; this stage is called the flooding zone. Water management is crucial for PEMFCs and significantly impacts performance (Baz et al., 2024).

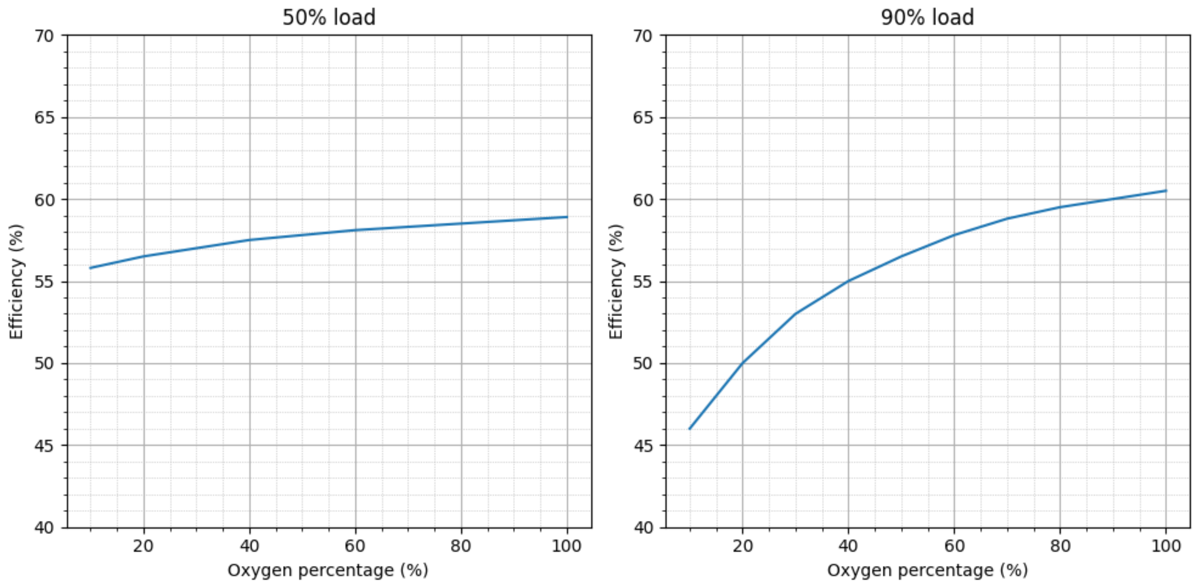

Figure 7 Effect of Oxygen Ratio at Two Different Loads on Efficiency.

The graphs in Figure 7 illustrate the effect of oxygen concentration on PEM modeling. At 50% load, with oxygen at 21% in the air, efficiency is 56%, while increasing O_2 enrichment level to 100% has only a small effect of 3%. At 90% load, with oxygen levels at 21%, efficiency increases by 10% when increasing from 50% to 100%. These results demonstrate that oxygen concentration affects efficiency under high load conditions, and no intervention is necessary within the optimum load range. This confirms the hypothesis of the study.

4. Results and Discussion

Hydrogen energy is a strong candidate to respond to the world's depletion of fossil fuels and the search for alternative energy sources. As population growth and rapid industrialization increase, non-renewable fossil fuels are dwindling daily while demand rises. According to a 2022 report by British Petroleum (BP, 2022), considering the ratio of total proven oil and natural gas reserves to annual production, only 50 years' worth of fossil fuel reserves remained in the world as of the beginning of 2020. Given its environmental impact on carbon emissions, hydrogen energy will become a very important player as its efficiency increases with developing technology. Improving the efficiency of fuel cells is crucial due to the high cost of current conditions. Hydrogen, as a fuel, is produced through electrolysis, and its production requires energy. Since liquefying or storing hydrogen in high-pressure tanks for transportation and storage is also costly, increasing its efficiency is essential.

In this study, the importance of oxygen concentration for PEMs operating under high loads has been demonstrated through modeling. Furthermore, it has been graphically shown that O_2 levels do not significantly contribute to efficiency at optimum loads. In an environment where the oxygen concentration in the air is 21%, it has been observed that increasing the oxygen concentration does not significantly contribute to efficiency when the PEM is operating at optimum load. However, since more oxygen is required at the cathode when operating under high load, increasing the O_2 enrichment level from 21% to 100% increases efficiency by approximately 10%. Additional elements can be used to provide pressure to increase the effect of high oxygen concentration on the cathode inlet surface area. This pressurization process can be achieved with turbo compressors or their derivatives.

Under normal conditions, in an air inlet with a 21% O_2 ratio, the water formed on the membrane evaporates before being expelled. As the temperature increases, the vaporization of this water also increases; as the water vapor mixes with the inlet air, the effective O_2 concentration becomes lower, which reduces efficiency. Mench reported that the energy gain resulting from the increase in temperature becomes neutral due to the decrease in effective oxygen concentration. Furthermore, Mench argues that the pores of a hydrogen fuel cell operating at very high temperatures will be clogged by water vapor, and this clogging can be prevented by feeding with high-concentration or pure oxygen (Mench, 2008).

Figure 8 shows the efficiency-oxygen concentration graph at all loads from 50% to 90%. This graph highlights that the initial efficiency decreases as the load increases, but the efficiency reaches acceptable levels as the oxygen concentration increases. Simulation results show that the loss drops to zero at 73% oxygen concentration.

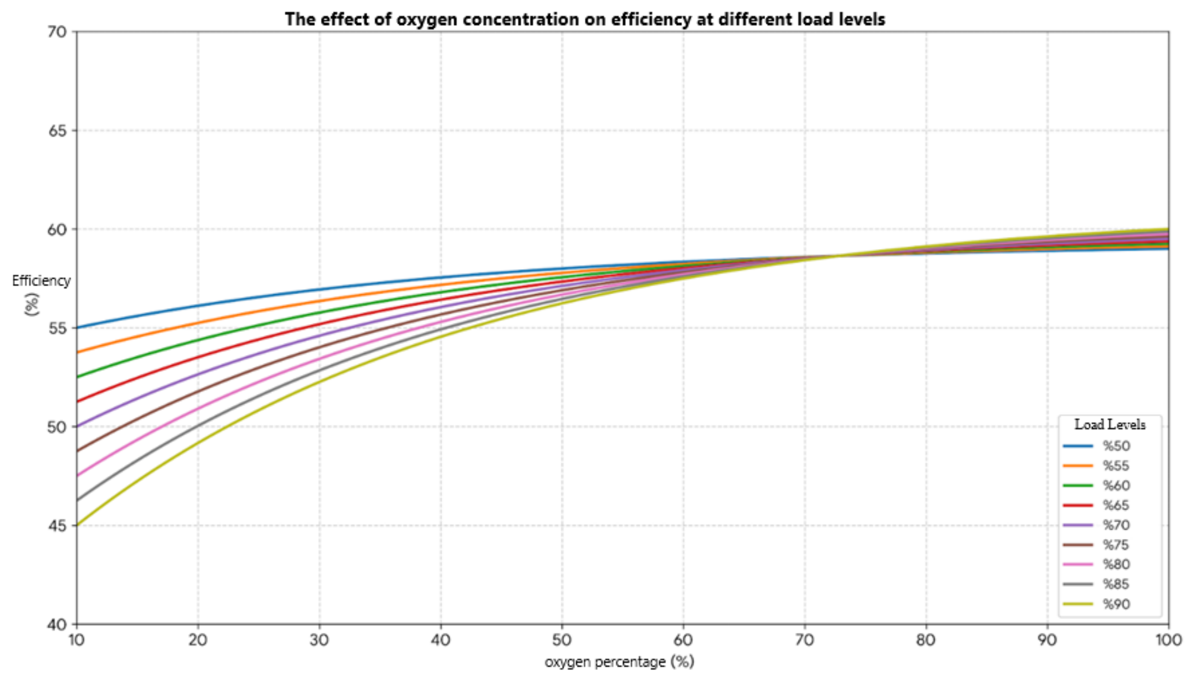

Figure 8 Efficiency vs. Oxygen Concentration at Various Load Levels

5. Conclusions

At high loads, increasing the O_2 enrichment level increases the rate of action of the gas on the catalyst section, preventing a sudden voltage drop. Because the voltage drop is prevented, fewer cells are needed for stacking; this reduces the weight and volume of the fuel cell. The lightness and small size of the fuel cell are of great importance, especially in aviation where weight savings are crucial. In addition to using pressurized oxygen, increasing the surface area of the cathode section will also increase efficiency. Increasing the cathode surface area requires a higher concentration and denser oxygen. A high load for a PEM varies depending on its capacity; for example, a cargo ship might use a fuel cell to transport tons of cargo. The power required to move a loaded ship is very different from the power needed when empty.

Since there is no need to increase oxygen concentration when operating at 50% load, using normal air while supporting the PEM with large-diameter, high-pressure oxygen cylinders easily accessible at the air inlet when activated at 90% load can significantly reduce concentration losses and increase efficiency by approximately 10%; this is supported by the simulation graphs in the study. In this context, this study will contribute to the literature for PEMFCs operating at high loads.

Based on the findings of this study, it is recommended that the method used be tested in future studies under different datasets, varying parameter ranges, and more complex scenarios. Furthermore, a comparative evaluation of the approach discussed in this study with different methods, diversification of performance criteria, and examination of its integration into real-time applications will increase the generalizability of the results. Considering practical factors such as hardware limitations, environmental impacts, and scalability will more clearly demonstrate the success of the method in real-world applications. Applying the results obtained in this study to different disciplines will allow for diverse contributions to the literature.

Declaration of Ethical Standards

As the authors of this study, we declare that this work complies with all ethical standards.

Credit Authorship Contribution Statement

C. Uğuz: Investigation, Conceptualization, Methodology, Software, Data curation, Writing – original draft, Visualization, Validation, Writing – review & editing

M. A. Şahman: Conceptualization, Methodology, Writing – original draft, Visualization, Validation, Writing – review & editing, Supervision

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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The authors declare that generative AI was used for language editing and figure enhancement, and not for scientific content generation. The authors would like to thank Lema Engineering, Construction, Electrical, Manufacturing, and Trading Ltd for their valuable support and contributions to this study.

Data Availability

This study is based on simulation/model outputs generated in MATLAB-Simulink; no external dataset was used.

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