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Research Article

Investigating the Impact of Hydrogen Gas Moisture Content on Electricity Generation in PEM Fuel Cells

Berat Fırat Dalğıç[1], Selman Aydın[2*]

[1] Koluman Otomotiv Endüstri A.Ş., Mersin, Turkey. (e-mail: bfiratdalgic@gmail.com).
[2*] Batman University, *Vocational High School of Technical Sciences*, Department *of Mechanical and Metal Technology*, Batman, Turkey. (e-mail: selman.aydin@batman.edu.tr).

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Corresponding author: *Selman Aydın*

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ABSTRACT

In the realm of energy sources, non-renewable fossil fuels, such as petroleum derivatives, continue to pose a significant threat to our planet. Currently, hydrogen energy, derived from renewable sources, is under extensive research, primarily due to its high efficiency, versatile applications, and zero carbon emissions. Hydrogen gas has become an indispensable alternative energy source owing to its numerous advantages. The technology that enables efficient utilization of hydrogen gas as an energy source is fuel cells, with Polymer Electrolyte Membrane Fuel Cells (PEM Fuel Cells) being the most significant advancement in this field. In this study, anode and cathode moisture levels were investigated by experimental study on the obtained efficiency of PEM fuel cell performance. Pure hydrogen and oxygen gases were used in the anode and cathode sections of the experiment, respectively. The test stand and a 6 cell 35 watt fuel cell with 9 cm^2 active area were used for the test. Temperature and water accumulation, especially humidification in PEM fuel cells, can be achieved by keeping the hydrogen flow, oxygen flow and battery temperature under control. In the experimental study, the fuel cell humidification rate is gradually increased by keeping the flow and line temperature constant. 30% - 35% - 40% - 45% - 50% - 55% - 60% - 65% - 70% of the results obtained in the voltage, amperage and their effects on watts. As a result of the experimental study, humidification rate has a significant effect on the performance of PEM fuel cell. With the increased humidification temperature, the performance of the installed system increased significantly and nominal values were found. However, it is observed that the performance decreases after a certain period of time in the values higher than 60%.

1. INTRODUCTION

Fossil-derived non-renewable fuels, when used as an energy source, contribute significantly to environmental pollution by releasing high amounts of carbon into nature, leading to diseases such as cancer.

Moreover, considering the limited reserves of these resources, alternative ways for energy production have been explored, with renewable energy sources emerging as the most crucial solution. These sources, including solar, wind, geothermal, and bioenergy, are not only renewable but also environmentally friendly, causing minimal harm to the environment [1]. The amount of energy that humans require today is growing daily. PEM fuel cells create a substantial amount of energy. Thus, efforts to improve this fuel cell's efficiency are still ongoing.

Currently, one of the most extensively researched energy types worldwide, including our own studies, is hydrogen energy. Fuel cell technology enables the most efficient utilization of hydrogen gas for energy production. Fuel cells operate with a simple and compact system compared to other energy systems. They generate direct electric current through a chemical reaction without the need for the combustion of hydrogen and oxygen gases, producing only pure water and low heat as byproducts. This heat is dissipated as the fuel cell's surface temperature, making it eco-friendly. The absence of moving parts and the presence of only gas inputs and outputs make fuel cells silent and, most importantly, safe. To generate more energy, multiple fuel cell units must be connected in series or parallel since the voltage of a single fuel cell unit ranges from approximately 0.9 to 1 volt. In the literature, this arrangement is referred to as a fuel cell stack [2].

Currently, Polymer Electrolyte Membrane Fuel Cells (PEM Fuel Cells) are considered the most important technology. Due to their portability, compact size, lightweight, high efficiency, lack of moving parts, and straightforward operation, almost all recent studies have been conducted on PEM Fuel Cells.

However, the use of a membrane with drying properties in the internal structure of PEM Fuel Cells leads to the formation of porous structures in the membrane, accelerating its degradation. It is reported that increasing the moisture content of hydrogen and oxygen gases supplied to the membrane enhances its durability and significantly impacts the fuel cell's performance.

This article presents experimental studies on the effects of gas moisture content on fuel cell performance. The results obtained are presented graphically.

2. LITERATURE SUMMARY

Choi (2017) developed the water and thermal management of Proton Exchange Membrane (PEM) fuel cell in this study. They established a bubble humidification system, one of the Balance of Plant (BOP) systems, to control the humidity, a critical factor of the fuel cell. The proposed fuzzy control system significantly increased the efficiency of the PEM fuel cell's output power [3].

In their study, Wang et al. (2003) experimentally investigated the effects of various operating parameters on the performance of PEM fuel cells using air on the cathode side and pure hydrogen on the anode side. The experiments demonstrated the impact of different fuel cell operating temperatures, cathode, and anode humidification temperatures, as well as different operating pressures on the PEM fuel cell performance through V-I curves [4].

İçingür (2011) conducted a study focusing on the temperature, pressure, and humidification parameters that enhance the efficiency of PEM fuel cells suitable for use in cars. Two fuel cells were designed, one made of aluminum and the other made of stainless steel, both utilizing a Nafion 115 membrane. The aluminum fuel cell achieved a maximum voltage of 2.98 volts, while the stainless steel one reached 3.12 volts in the experiments [5].

Eker (2012) utilized Fluent PEMFC module for simulation and experimental studies, comparing the results. The study compared the effects of humidification temperature, hydrogen, and oxygen flow rates on the system's efficiency. It was observed that increasing the humidification temperature significantly improved the system's efficiency. However, after a certain level, the efficiency remained constant and started decreasing as the temperature further increased [6].

In his experimental study, Yılmaz Ulu (2010) established a hybrid solar energy system. The equipment used in the system was analyzed in detail through energy production calculations. The electrolyzer's performance was 54.4%, and the energy efficiency ranged from 28.1% to 42.2% [7].

In a laboratory setting, Çelik (2006) generated energy by directly using sodium borohydride. Recommendations were made regarding the production of different plates and pipes made of durable materials with good conductivity, such as 304 stainless steel. [8].

Kaplan (2008) used Nafion 115 membrane, 304 stainless steel wire for the anode and cathode, and copper wire for the catalyst in his experimental study. The power obtained from the fuel cell was examined, and it was observed that the power value of the copper catalyst used was lower than that of platinum [9].

Ateş (2008) designed an algorithm using artificial neural networks, focusing on the control of a hybrid fuel cell/ultra-capacitor vehicle's energy system. The control algorithm aimed to optimize the regular state for the fuel cell content, enabling the fuel cell system to meet the required load demand and respond to instantaneous load changes, as well as recover energy from the braking system [10].

Keskin (2014) integrated the energy control system into a PEMFC/Battery vehicle system. The application was designed to handle sudden load differences and recover excess energy during braking. The dual-sided DC-DC converter added extra cost to the system, but it significantly improved the system's efficiency and performance values [11].

In his study, Bilen (2015) developed a highly efficient electrolyzer by using pure water, aiming for a more economical hydrogen production method. The distance between the electrodes and increasing the electrode system's surface area were found to increase hydrogen production, as confirmed by theoretical calculations. However, it was observed in experiments that excessive electrode spacing led to decreased conductivity, resulting in reduced production [12].

Efendioğlu (2013) prepared a data system in line with the data obtained from his project for the "Response Surface Methodology of Central Compound Design," one of the five sections of his study. The study showed that the "Rate" factor significantly affected the "Power Density" at α=0.05 significance level [13].

Türe (2006) compared the analysis of a hydrogen system operating with a photoelectrolysis cell, producing hydrogen from photovoltaic systems at 10% efficiency. Photoelectrolysis was considered the most efficient and economical production method among renewable energy sources. The high efficiency and economic viability of hydrogen production led him to combine the photovoltaic system, directly converting solar energy into electricity, with an electrolysis system using a semiconductor photoelectrode. Utilizing renewable and environmentally friendly hydrogen energy is essential for transitioning to hydrogen energy, and more studies should be conducted in this field [14].

In their study conducted abroad, Alnıak, Karakaya, et al. (2008) examined the production of hydrogen gas storage tanks. However, such studies in our country have not gained commercial recognition, and many designed projects have remained in the experimental project phase. This study primarily investigated the production of a high-pressure hydrogen gas storage tank made of aluminum. Various methods of manufacturing these tanks and their usage areas were examined. The experiments resulted in obtaining three different aluminum tanks in various sizes, using three different Aluminum 6000 series. Despite numerous challenges faced during the production stage, the designed tanks were subjected to a hydrostatic pressure test. Ongoing research focuses on suitable materials, storage tank forms, and other related topics [15].

In his study, Muhtarlıoğlu (2012) designed an environmentally friendly system capable of charging portable and lightweight electronic devices such as smartphones, utilizing solar energy to convert it directly into electrical energy. This system consisted of solar panels, charge control parts, and batteries. The solar panel converted solar energy into electrical energy in DC form. To enable the system to be utilized when sunlight is insufficient or absent, a battery was used. Charge control units were added to prevent the battery from overcharging or discharging excessively and to maintain a constant voltage value. These control units allowed real-time monitoring and control of transmission parameters through a user-friendly interface [16].

Silver (2008) synthesized an effective and inexpensive catalyst for the electrocatalysis of the Oxygen Reduction

Reaction (ORR) in the cathode part of PEM fuel cells. The study introduced alternative catalysts, PtCuFe/C-611, and PtAgFe/C-611, for the cathode section of PEM fuel cells [17].

Oral (2005) designed a theoretical model to determine the effects of selected fundamental parameters on the Proton Exchange Membrane (PEM) fuel cell. The study aimed to determine the optimal value range by identifying the influences of certain basic parameters on a theoretically designed model. It was observed that air pressure was the most effective parameter in the designed model, significantly enhancing performance. However, a significant decrease in performance was observed when the compressor was disengaged at an approximate pressure of 1 bar. After 1 bar pressure, the performance levels ranged between 55% and 76%, indicating a substantial increase in performance. These achieved performance levels were the best in the model, demonstrating that air pressure was the most influential parameter [18].

3. MATERIALS AND METHODS

3.1. The Installation of Proton Exchange Membrane Fuel Cell System

Recent studies on PEM fuel cells have shown significant impacts on the efficiency and performance of the fuel cell system due to changes in parameters such as gas humidity, pressure, temperature, and flow rate. These changes affect the choice of membrane, catalyst, gas diffusion flow layer, flow channel variations, and other parameters. Additionally, excessive water in anode and cathode pipes can block pores and increase gas transfer resistance, leading to a decline in performance. Interestingly, in such fuel cells, it is necessary to both humidify the gases and remove accumulated water between the cells. Maintaining ideal humidity levels is a challenging task for all system conditions. Therefore, effective water management is crucial for PEM fuel cells to achieve high performance. Optimal parameters for the implemented systems need to be determined [20].

In this study, experimental research has been conducted on the effects of gas humidity on fuel cell performance. These experimental parameters were tested in a computer-assisted environment at TÜBİTAK-MAM Renewable Energy department, and the results were compared with differences observed in the system designed at the Batman University Technology Energy Systems Engineering Department Laboratory. The results obtained were compared, and the influence of humidity parameters on PEM Fuel Cell performance and efficiency was analyzed. Furthermore, to assess the performance and efficiency of these cells, simulations were conducted using the Fuel Cell 3 commercial software in a computer environment. The humidity levels of gases used in PEM fuel cells were measured using power, current, and voltage values recorded by measurement devices over time. The findings of these humidity-related investigations were presented in graphs and tables.

The experiment involved supplying hydrogen and oxygen gases to the system at appropriate levels after the setup of the PEM fuel cell. These gases were humidified, and the experiment was concluded. The experiment was conducted using the system established in the Batman University Technology Faculty Laboratories and tested in the TÜBİTAK Renewable Energy Laboratory. Additionally, the data were analyzed in a computer environment, and evaluations were made accordingly.

Study of Barbir, a PEM fuel cell produced with "Fuel Cell 3" technology was used. The fuel cell can generate a variable power demand with a maximum value of 35 W and consists of 24 MEA cells covering a total electrode area of 45 cm². The performance of the fuel cell was measured by changing the DC electronic load, and the generated data were recorded. Based on the evaluations, the optimal humidification temperature for achieving maximum power in the PEM fuel cell was determined [19].

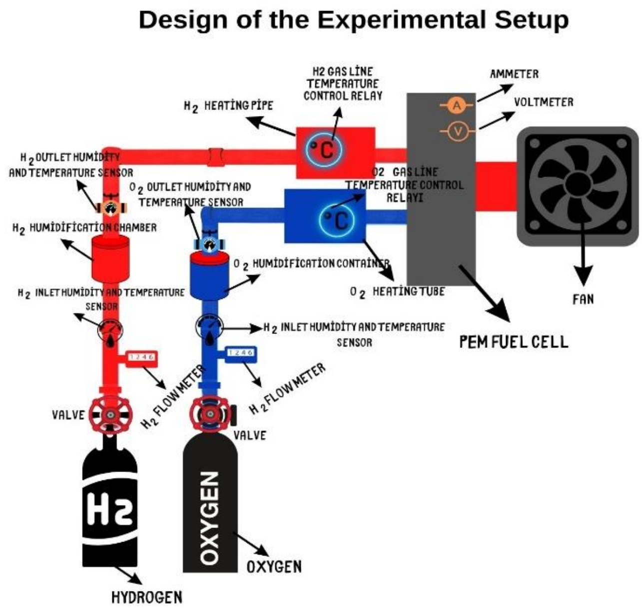

Figure 1. Schematic View of PEM Fuel Cell Experimental Setup

This project involved the successful installation of equipment and materials, provided by the project team, onto the experimental setup in the Renewable Energy Systems laboratory of Batman University Technology Faculty. Additionally, a portion of the experiment was conducted at Ankara TÜBİTAK Renewable Energy laboratory, where all stages of the test were completed successfully.

Figure 2. Data recording and testing device at TÜBİTAK MAM facility

3.2. Experimental Procedure Steps

1. The system design was initially drafted in a computer environment.
2. A list of required materials was compiled, and the materials were procured.
3. Pneumatic pipes were used to connect the Oxygen and Hydrogen cylinders to the flow meters.
4. Connections were established from the output points of Oxygen and Hydrogen flow meters to the humidification tubes via pipe connections.
5. Electronic humidity sensors were connected to the input and output points of oxygen and hydrogen humidification tubes.
6. Copper pipes, which would connect to the output pipes of Oxygen and Hydrogen humidification tubes, were procured and bent as necessary.
7. After bending the output pipes of Oxygen and Hydrogen humidification tubes, they were covered with heating bands and insulating material, and the necessary electrical connections were made.
8. Electronic thermometers were placed inside the copper pipes with heating bands for Oxygen and Hydrogen, and temperature control relays were installed to adjust and maintain the temperature.
9. These copper pipes' output points, i.e., the outlets for Oxygen and Hydrogen, were connected to the PEM Fuel Cell.
10. Voltmeter and ammeter, along with data logger and measurement devices, were attached to the PEM Fuel Cell transmission circuit for measurement purposes.
11. A fan was installed to regulate the temperature of the PEM Fuel Cell.
12. The system is up and running.

4. RESULTS AND DISCUSSIONS

In this section, the experimental setup we designed for the moisture-dependent variations of PEM fuel cell is described. The purpose was to observe the effects of moisture on efficiency using our PEM fuel cell system. The experimental method and the results obtained from the experiment are explained. We operated the P.E.M. fuel cell experimental setup, which we installed in the Batman University Technology Faculty laboratory, for a considerable period and stabilized it. Then, Hydrogen and Oxygen gases were gradually introduced into the system through the flow meters. The energy parameters of the system were observed. These observational data were recorded, graphed, and extensively analyzed using the Fuel Cell 3 commercial software. Parameters like moisture, flow rate, temperature, and line temperature were thoroughly examined, and optimal nominal values were determined.

Our P.E.M. fuel cell has a standard size consisting of 3×3 cells. However, due to membrane burning and piercing incidents in 5 of the cells during the experiment, the experiment continued with a single cell.

- P.E.M. Fuel Cell Temperature: 41°C
- Current: 1.8A, Hydrogen (H2): 300 ml/min, Oxygen (O_2): 500 ml/min

After setting the values at their optimal positions, the moisture temperatures of hydrogen and oxygen channels were gradually increased while keeping them stable. The efficiency results of the fuel cell were graphically obtained.

In the experiments, the 6-cell fuel cell used in our P.E.M. experimental setup in the Batman University Technology Faculty laboratory was tested. Initially, as mentioned before, 5 cells were used due to the burning of one cell. For the purpose of verifying the accuracy of our values, the single-cell version of our fuel cell was taken to TÜBİTAK's Renewable Energy Laboratory in Ankara and tested only for this purpose. The values obtained in our self-designed system at Batman University were almost identical to the results obtained during the tests. The experiments were conducted at humidity levels of 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, and 70%, respectively. According to the data in Table 1 and Figure 3, we see the volt, ampere and watt values per cm^2.

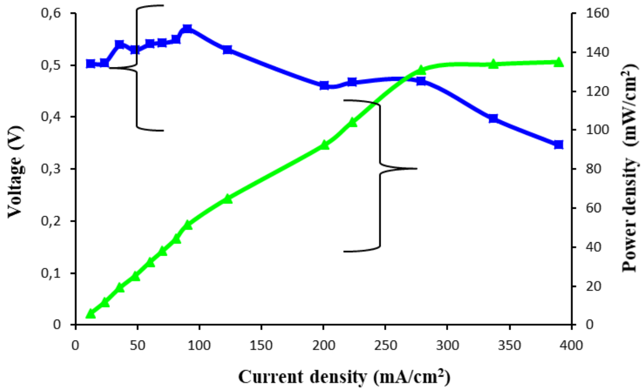

Figure 3. Voltage, current and power polarization curve on unit cm^2 area due to humidity change in PEM fuel cell

TABLE 1. VOLTAGE (VOLTS), CURRENT (AMPERES), AND POWER (WATTS) PER CM^2 DEPENDENT ON PEM FUEL CELL

Voltage	Current	Power	mA/cm^2	Voltage	W/cm^2
0.503	0.11	0.05533	12.22222	0.503	6.147778
0.505	0.21	0.10605	23.33333	0.505	11.78333
0.539	0.32	0.17248	35.55556	0.539	19.16444
0.529	0.43	0.22747	47.77778	0.529	25.27444
0.541	0.54	0.29214	60	0.541	32.46
0.543	0.73	0.40077	81.11111	0.549	44.53
0.57	0.81	0.46176	90	0.57	51.3
0.53	1.105	0.58565	122.7778	0.53	65.07222
0.461	1.807	0.83302	200.7778	0.53	65.07222
0.467	2.01	0.93867	223.3333	0.467	104.2967
0.47	2.507	1.17829	278.5556	0.47	130.9211
0.398	3.03	1.20594	336.6667	0.398	133.9933
0.347	3.507	1.21692	389.6667	0.347	135.2143

The experiment was initially conducted with fixed values of hydrogen flow rate at 0.3, oxygen flow rate at 0.5, and cell temperature at 41°C. After operating in this stable condition for a day, gradual changes were made to other parameters, and data collection commenced. In the experiment, humidity levels were gradually increased to values of 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, and 70%, respectively.

When observing the effect of moisture:

- Anode input gas flow rate (H_2): 0.300 l/min
- Cathode input gas flow rate (O_2): 0.580 l/min

- Current: 1.8 A were kept constant.

The obtained Watt-Volt and humidity values from the experiment are outlined below:

a) At 30%, we observe 0.432 V – 0.778 W.

b) At 35%, the values are 0.501 V – 0.901 W. Here, we witness a sudden increase in our fuel cell's stability and efficiency, which is a crucial observation. During our experiment, seeing our fuel cell, which we worked hard to stabilize over 24 hours, suddenly become efficient indicates that our efforts were successful.

c) Progress remains steady between 35% and 40%.

d) At 45%, the values are 0.922 V – 0.512 W, indicating another increase.

e) At 50%, we observe a slight decrease, marking a turning point for further increases. Our Watt value stabilizes within a specific range, and this observation is a significant finding. The Watt value and its corresponding Volt value rise up to a point, then exhibit fluctuations but overall remain stable.

f) The humidity level rises to 60%, and afterward, it shows a continuous decline trend. Voltage and power values rise initially, then begin to decrease, followed by another increase, and stabilize. In other words, at 60% humidity, we achieve the highest power and voltage values, recorded as 0.514 Volt, 1.8 Amperes, and 0.954 Watts.

g) Values obtained after 60% are at 65% and 70%. At 65%, the efficiency is 0.525 V – 0.945 W, and at 75%, the efficiency is 0.52 V – 0.936 W. However, what we observe from these values is that the cell stabilizes, operates steadily, and there won't be significant changes in temperature regardless of any subsequent additions.

5. CONCLUSION

As a result of our studies, the effects of the moisture parameter on the performance of PEM fuel cells have been investigated. In this study, consecutive tests were conducted at specific intervals to stabilize the fuel cell based on joint experiments conducted at Batman University and TÜBİTAK Renewable Energy laboratories. During these tests, the membrane of 5 fuel cells was pierced due to water accumulation inside the cells, caused by high humidity, rendering them unusable. Detailed images and diagrams related to this issue are attached. After this stage, experiments were continued with a single-cell PEM fuel cell at the TÜBİTAK Renewable Energy Laboratory.

During the experiments:

- Anode input gas flow rate (H_2): 0.300 l/min
- Cathode input gas flow rate (O_2): 0.580 l/min
- Current: 1.8 A

After being kept constant at these values, moisture levels were gradually increased to %30, %35, %40, %45, %50, %55, %60, %65, and %70, respectively. When evaluating the data obtained from the experiment:

In the power (watt) values, there was initially a good increase (0.123 W), followed by a period of stability, and then another increase of 0.021 W was observed. Upon further examination, a decrease occurred at a certain point. The highest efficiency obtained was 0.954 Watt at 60%, which was recorded as the highest electrical power value obtained from the experiment. However, we believe that this efficiency would further increase if water formation within the plates (membrane) is prevented. Since all cells are interconnected, the formation of water affects the entire fuel cell, hindering the acquisition of watt and volt values. To achieve the desired efficiency, it is essential to work with robust membranes and prevent water formation. We believe that if our suggestions are taken into account, the energy efficiency of the fuel cell can be further improved, making significant contributions to other experiments.

Today, the energy needed by humanity is increasing day by day. The energy produced by pem fuel cells is at a significant level. Therefore, the search to increase the efficiency of this fuel cell continues. In this study, positive results were found as a result of the investigation of humidity in PEM fuel cells. In future studies, it is very important to continue studies to increase the efficiency of the PEM fuel cell.

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BIOGRAPHIES

Berat Fırat DALĞIÇ was born in 1990 in Diyarbakır/Turkey. He graduated from Mersin University Mechanical Engineering Department in 2014, which he earned in 2010. During his university years, he participated in the Formula G and Electro-Mobile competitions organized by TÜBİTAK every year, by producing 4 efficient vehicles with the ANKA Alternative Energy Team. In 2016, he started his master's degree in Batman University, Institute of Science and Technology, Department of Renewable Energy Systems. In his working life, he worked at Onalsan Çatı, Essante, Stilteks Metal and Dal Mühendislik Group, respectively. Nowadays, Koluman Otomotiv Endüstri A.Ş. He works as a System Specialist in the Military Projects Directorate.

Selman Aydın was born in Batman, Turkey. He graduated from the Dicle University Technical Education Faculty Automotive Teaching B.Sc. degree between 2000-2004. In 2008, he started his M.Sc. degree at Fırat University Institute of Science and Technology, Department of Mechanical Education/Automotive. In 2010, he graduated with an M.Sc. degree. In 2010, he started his Ph.D. at Marmara University Institute of Science and Technology, Department of Mechanical Education. In 2014, he graduated with a Ph.D. Between 2012-2015, he worked as a lecturer at Hakkari University, Department of Mechanical Engineering/Automotive. In 2015, he started to work as an assistant professor in the Batman University Faculty of Technology, Department of Automotive Engineering. In 2020, he received the title of associate professor in the field of automotive engineering. In 2021, he was appointed as an associate professor at Batman University Vocational High School of Technical Sciences. He is currently working as an associate professor in the same unit. Major research interests are internal combustion engines, engine dynamics, alternative fuels, fuel cells, and automotive engineering. He has published more than 50 papers in international and national journals and conferences.