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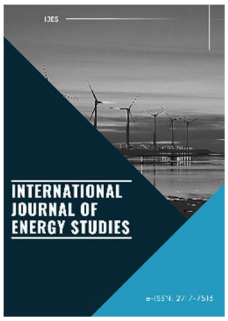

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Experimental investigation of bio-inspired flow field design for AEM and PEM water electrolyzer cells

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Highlights

- Investigation into the influence of flow fields on electrolyzer system performance through integrated fluid dynamics mathematical models.
- Evaluation of a bioinspired flow field design for enhanced electrolyzer functionality.
- Preparation of electrodes utilizing carbon-supported Pt catalysts.
- Comparative analysis of Proton Exchange Membrane (PEM) and Anion Exchange Membrane (AEM) electrolyzer systems.

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ABSTRACT

Hydrogen is the strongest candidate to become the future fuel of the world to meet net-zero targets while it cannot be found in nature in pure form and the most major occurrence is in water or carbon-based forms. Therefore, external energy is needed to retrieve hydrogen in pure form where natural gas reforming is the most common method for over 90% of hydrogen production worldwide with carbon footprint followed by water electrolysis which is environmentally friendly. As clean methods PEM and AEL electrolysis are mature technologies while AEM takes increased attention with its unique dry cathode technology. This study examines how a nature-influenced (Bioinspired) and a serpentine flow channel design affects PEM electrolyzer and AEM electrolyzer cell functionality. The performance of the electrolyzers is assessed in terms of experimental polarization curves. It was decided to utilize Sustainion® XA-9 Alkaline Ionomer Powder as the ionomer solution and Fumasep FAS-50 as the membrane. The laminar flow analysis is performed using COMSOL Multiphysics. The efficiency of the PEM electrolyzer is 71% with the serpentine flow, while the efficiency is 73% with the biomimetic flow. The efficiency of the AEM water electrolyser is 25% using the same design. The low performance in AEM was interpreted as the inability to distribute the catalyst homogeneously on the membrane surface.

Keywords: Renewable energy, Hydrogen, Electrolysis, Electrolyzer, AEM water electrolysis, Bio-inspired flow field design, PEM water electrolysis

1. INTRODUCTION

In the modern world, the widespread use of fossil fuels and the number of carbons produced during their combustion contribute to pollution and global warming. This is why efforts are being made to boost the use of alternate renewable energy sources. The primary sources of renewable energy include solar energy, wind energy, geothermal energy, and wave energy. The curtailed energy cannot be stored since the electrical energy from these sources is directly linked to the grid and limited to demand. Additionally, renewable fuel is required as a substitute for natural gas for heating and supplying heat to systems using current cycles. Hydrogen fuel can be used as a clean energy carrier and backup energy source in this scenario. Hydrogen is created from water using electrolysis. Alkaline and PEM electrolyzers, sometimes referred to as hydrogen generation from water, are matured and widely used. Alternative systems like synthetic photosynthesis electrolysis systems and solid oxide electrolyzer systems are still being investigated at lower TRL levels.

Alkaline electrolyzers are well-developed and often used in industry, however, they have low power densities (100–800 mA/cm2) and low efficiency (60–70%). Despite PEM electrolyzers' recent commercialization and widespread use due to their high efficiency (70–80%), they are extremely costly devices since they require catalysts like Pt and Ir. Anion Exchange Membrane Electrolyzer = "Anion Exchange Membrane Water Electrolysis" (AEMWE) systems, which operate with the same high efficiency as PEM electrolyzers but with less expensive anode and cathode electrode materials than PEM electrolyzers, appear promising in recent years [1]. The AEMWE cell was created as part of this research and its efficiency was compared to a PEM type electrolyzer of the same size.

Xu et al. made a literature review on AEM water electrolyzers and gave information on the cell type, the catalysts used and the working principles of the cell [1]. Additionally, Park et al. investigated the Catalyst Coated Membrane (CCM) and the Catalyst Coated Substance (CCS) techniques for the catalyst coating method. Through their research, they discovered that applying the CCM yielded improved results [2]. In a similar study, Ito et al. looked at the CCM and CCS methods and found that the CCM method performed better than CCS [3].

There are many research papers about flow channels in fuel cells and electrolyzers. The study investigates a PEM water electrolyzer, comparing serpentine and parallel designs. Rho et al. [4] studied the excess potential distribution and the oxygen/hydrogen velocity fractions to understand

their effects on current density. Ozden et al. explored nature-inspired flow paths and examined how leaf-like designs affect Direct Methanol Fuel Cells [5]. Toghyani et al. simulated five flow fields for PEM fuel cells. They then compared the models' pressure drop, uniform temperature distribution, current density, and hydrogen output [6]. Kahraman and Orhan analyzed some existing flow channel designs, therefore, they made some suggestions that fuel cells' performance and production cost can be reduced for their specific duties [7]. Lim et al. investigated the pressure and speed of some parallel flow models were studied. To observe the pressure distribution in different regions of the flow, they modeled it in computational fluid dynamics software [8]. Friess and Hoorfar compared the impact of radial flow channels on pressure drop and battery performance against other traditional flow channels [9].

Using Ni-based catalysts on the cathode surface of AEMWE instead of Pt/C catalysts shows a conducted study suggesting that achieving AEM water electrolysis performance at commercially important levels (especially in terms of cost versus current) is feasible. [10]. Pavel et al. reported a highly efficient design for alkaline polymer electrolysis, utilizing a membrane-electrode assembly (MEA) based on low-cost transition-metal catalysts and an anion exchange membrane (AEM) [11]. Ahmed et al. examined NiO, NiFeOx, and NiFeCoOx catalysts in AEM water electrolysis, highlighting NiFeCoOx's superior performance, reaching 802 mA cm-2 at 2 V and 70°C due to Co and Fe synergistic promotion. The study emphasized the substantial impact of electrolyte concentration, revealing a peak activity of 954 mA cm-2 at 2.1 V with 1 M KOH and superior performance with the X-37-50 membrane, which demonstrated 1.62 times higher current density compared to FAA-3-50 under similar conditions [12].

The membrane is as crucial as the catalysts' activity. Gatto et al. found that longer ion exchange times weaken membrane properties. This highlights the significance of optimizing ion exchange durations for stronger Anion Exchange Membrane Water Electrolysis (AEMWE) membranes and enhanced MEA efficiency. [13]. Using the catalyst-coated membrane method with the FAA3-50 membrane enables operation at higher temperatures. However, it was noted that in this setup, the cell needed a constant supply of KOH solution to function at these elevated temperatures [14]. Vincent et al. innovatively developed a cost-effective membrane electrode assembly (MEA) for AEM electrolysis, utilizing the A-201 AEM and non-noble transition metal oxides as catalysts. Their optimized oxygen evolution reaction (OER) demonstrated superior performance with a

reduced catalyst loading of about 30 $mg_{cat}cm^{-2}$, surpassing reported values and significantly lowering costs compared to conventional precious metal-based catalysts [15].

2. EXPERIMENTAL

2.1. Design of a Single-Cell Electrolyser

Trees have the best inspiration flow channels in nature. Tree roots send water to its trunk, which then sends it to its branches, which then sends it to its leaves. Water and nutrients are delivered to the leaf through capillary tubes in the leaves. This is necessary for the leaves to survive. The leaves wouldn't stay put if the water were being delivered with too much pressure. The water that needed to move from the water to the cells in the leaf would travel into the channels if the liquid entering the leaf moved too quickly. Eventually, the leaf would die.

It has been reported that high performance is achieved when the design used in the literature review is used together with the serpentine flow channel in the PEM fuel cell [5]. It was noticed that this study was not tested on electrolyzers or Anion Exchange membranes. Its design was also tested in this study to see if it would provide the same effect in electrolyzer units.

Tree leaves and designs found in the literature served as inspiration for the design. Water pressure and speed are controlled by angular expansions and contractions in the channels on the upper and right sides. 1 mm channel widths and 0.5 mm rib spacings were recommended. Given that the cell's active area is 5 cm^2, the interior width and length are 22 mm. Additionally, 1 mm was determined to be the ideal channel depth. Deionized water and a 1 molar solution of KOH were believed to pass through without crystallizing. The variations in this design are revealed by the polarization curves. A Laminar Flow analysis was additionally carried out to get results using COMSOL multiphysics. The Biomimetic Flow Field Design prepared using stainless steel is shown in Figure 1.

Figure 1. Manufactured biomimetic flow field design for 5 cm^2 active area

Figure 2. Serpentine flow field design for 5 cm^2 active area

Following performance testing, the Biomimetic flow field plates are attached to both sides of the PEM electrolyzer in the initial phase of the investigation. As stated in the paper, performance testing will be used to link bipolar plates with biomimetic flow channels to the serpentine cathode side of the cell and determine polarization curves and efficiencies.

Niğde Ömer Halisdemir University used a cell with an active area of 5 cm^2, employing platinum and iridium as catalysts in a PEM electrolyzer. Iridium was used as the anode catalyst, while platinum was used as the cathode catalyst. The membrane material used was N115. Pt black loading for the cathode was 0.7 mg/cm^2. As an anode catalyst Ir-black (2.0 mg/cm^2) was applied. The catalytic composition for anode and cathode contained 15% wt of the ion-exchange polymer (with respect to the weight of catalyst) and was applied onto Nafion membrane by spray technique.

In this study, the prepared Membrane Electrode Assembly (MEA) was used for the PEM electrolyzer There is just one flow channel of the serpentine flow field (figure 2). The cell's insulated regions and seals, however, needed to be maintained because they had only been used once. The gaskets were initially taken out and placed in thinner. after removing the insulating substance that was stuck to it. Wrapping it with heat shrink tubing restored the insulation. To facilitate movement in the holes, the holes have also been increased by 1 mm. The surfaces were re-insulated with tape since the insulating material on the surface vanished due to the expansion of the holes in the end plate and current collector. On the anode side, titanium mesh and titanium porous layer were employed, while on the cathode side, titanium mesh and carbon paper were used. The design of a single cell with a 5 cm^2 active area, showcasing bipolar plates, MEA, current collectors, and end plates, is illustrated in Figure 3.

GDLs are typically constructed using porous conductive materials, and carbon-based materials are commonly used for this purpose. The carbon-based materials provide the necessary electrical conductivity and structural support for the overall function of the fuel cell. GDLs are typically designed as a bilayer structure consisting of a macro-porous backing material (carbon fiber paper support) and a micro-porous, carbon-based layer (MPL). These materials are chosen for their high conductivity, durability, and porous nature, which allows the easy flow of gases. The thickness of GDLs typically falls in the range of 100-400 micrometers. In this study, Toray's TGP-H-060, with a total thickness of 190 micrometers, was employed as the chosen GDL.

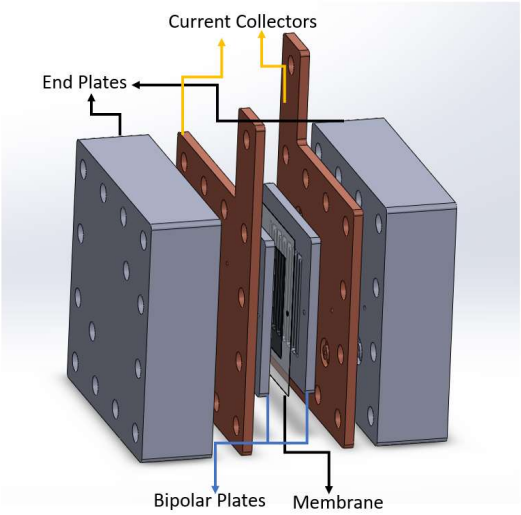

Figure 3. 5 cm^2 active area assembly design

A membrane and an additional new catalyst are required by the cell to replace its anion exchange membrane. An OH- permeable membrane is required because as mentioned the AEMWE study principle is OH- ions can traverse between the membrane. The recommended membrane was Fumasep FAS 50, which was obtained from the Fuel Cell Store. Sustainion® XA-9 Alkaline Ionomer Powder, which was chosen as the ionomer solution, was purchased from Dioxide Materials. The primary function of the ionomer solution is to let the relevant ions produced by the reaction cross. The ions should have developed here in an alkaline solution. To keep the OH- ions and convey them to the membrane, this solution was chosen. In AEMWE, differently from those used in PEM electrolyzers, a nickel porous layer is employed on the anode side, while carbon paper is used on the cathode side.

2.2. Preparation of Membrane and Ionomer Solution from Ionomer Powder

The Fumasep FAS-50 Membrane is immersed in a 1 molar KOH solution for 1 day, followed by rinsing with deionized water. Sustanion company sells the Sustainion® XA-9 Alkaline Ionomer powder commercially. The amount of Ethanol required to convert this powder into Ionomer wt 5% solution is 23.5 g.

2.3. Preparation of Ink

The catalyst material used for the coating is Pt/C 10% wt. We added 1 ml of deionized water, 0.74 g of catalyst material, 1 ml of Ionomer solution, and 10 ml of ethanol solution into a beaker. The reason we put deionized water and catalyst in the first place is that if we pour the ethanol directly onto the platinum, it will flare up. Mixing was carried out in an ultrasonic bath [10, 13, 14].

2.4. Coating Methods

There are two distinct coating techniques. The first technique, known as CCM, involves smearing catalyst ink directly over the membrane. The second technique is called CCS and it involves covering the electrode. Studies using the Catalyst Coated Membrane (CCM) approach have shown that more stable and efficient hydrogen generation occurs, and performance rises as it can create a stronger link between the membrane and the catalyst. On the other hand, they discovered that the CCS method's cell gap was lower than the CCM's performance. Although high temperatures caused anion exchange membranes to distort, a decline in their performance was still seen even though the CCS method was primarily employed to create a link between them utilizing the hot press technique. The appearance of materials used in the coating process is provided in Figure 6.

In the methodology employed in this study, two carbon sheets and one nickel foam have been used for CCS (figure 4). This carbon paper and nickel foam were then trimmed to 22 * 22 mm, and a heating plate was then attached using a brush at the bottom. The lowest temperature allowed the catalyst ink to dry in about 30 minutes. In addition, the hot press method was not used to protect the membrane from harm. conducted cold integration.

Figure 4. Photo of CCS coating process

2.5. Experimental Setup and Test Measurements of PEMWE

The experimental setup includes a water pump and an electric power source. In addition, water was placed in a graduated cylinder. To create a manometer, water was added to a plastic bottle, and then the graduated cylinder was flipped upside down and inserted into the bottle. The amount of hydrogen produced at a steady voltage in a minute was also measured through the pipe that was extended into the graduated cylinder. By holding the cell for 4 repetitions of 3 minutes, the goal was to attain the polarization curve. Polarization curves were obtained for PEMWE within the range of 1.5V to 2.4V, with increments of 0.1V. The membrane would have been harmed if the voltage had been raised to 2.5 Volts. In the first experiment, both flow channels utilized a biomimetic flow field. The voltage was then maintained at 2.1 Volts for a 9-minute measurement after the cell had stabilized. The graduated cylinder's scale intervals were used to compute the volume of produced hydrogen. The arithmetic average of the current values at the first, third, fifth, seventh, and ninth minutes was calculated since the current was not constant in the measurement data. By putting a Serpentine flow field on the anode side of the cell and a biomimetic flow field on the cathode side, the identical experimental methods were carried out once more. All the experiments were applied at room temperature.

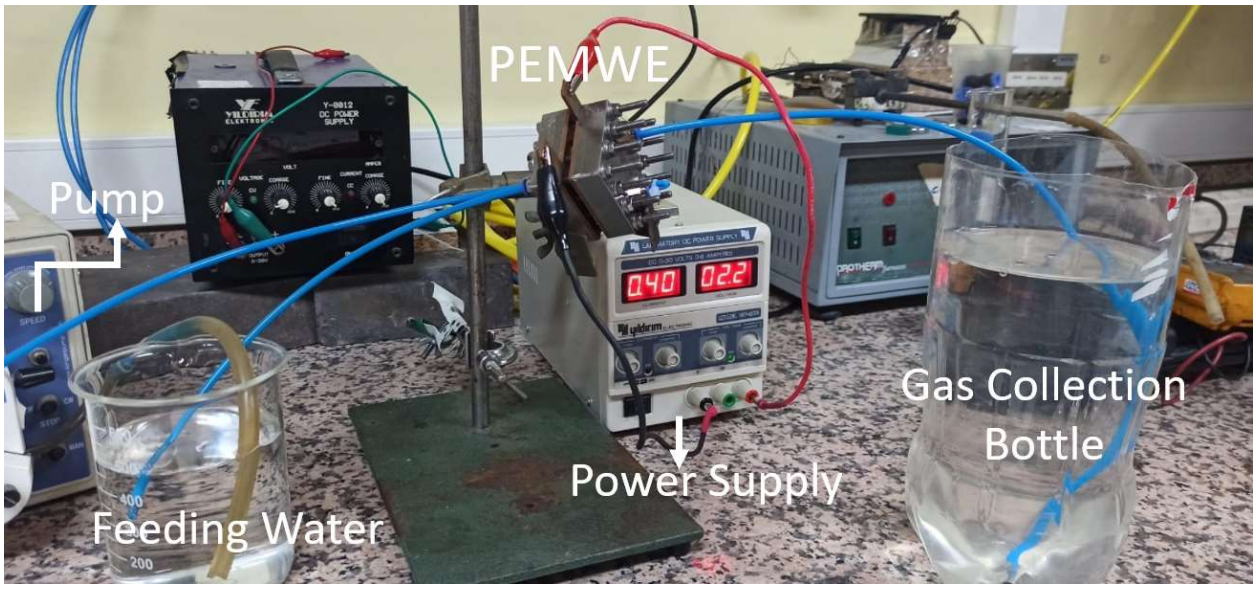

Figure 5. PEM electrolyzer experimental setup

2.6. Experimental Setup and Test Measurements of AEMWE

Anion Exchange Membrane water electrolyzer's working principle is different from PEM water electrolyzers. A 1 M KOH solution was injected into the cell's cathode area. Hydrogen evolved, and OH- ions moved to the anode portion. The oxygen evolution process occurred at this location, and the oxygen molecules exited the system. The cathode component discharges excess 1M KOH solution as well as hydrogen. Another mixing bowl was used in addition to the PEM electrolyzer while taking measurements. The reason for this is that KOH solution and hydrogen come out of the same pipe, so while the liquid is collected at the bottom, the gas can leave the system by taking advantage of the extra space above. Nickel foam is placed on the oxygen side, and GDL Carbon 1 is placed where the KOH solution enters. All the experiments were applied at room temperature. Polarization curves were obtained for AEMWE within the range of 1.5V to 2.2V, with increments of 0.1V.

Figure 6. Anion exchange membrane electrolyzer experimental setup

2.7. Mathematical Model

A Laminar Flow analysis was performed using COMSOL multiphysics. In this study, the simulation based on Brinkman equations showed more details about the velocity and pressure field. The Brinkman Equations Interface has the following domain, boundary, point, and pair nodes. The available Boundary condition options for an inlet are Velocity, Fully developed flow, and Pressure. Impermeability, no-slip, and no-flux boundary conditions are applied at all the internal surfaces within the modelling domain. Steady-state operating condition is assumed, with the gas flow considered to be laminar and incompressible due to low velocities. The equations solved by the Laminar Flow interface are the Navier–Stokes equations for conservation of momentum and the continuity equation for conservation of mass. By default the physics interface was used the Incompressible flow formulation of the Brinkman equations to model constant density flow.

3. RESULTS AND DISCUSSION

3.1. Analysis Results of the Biomimetic Flow Channel

To be able to perform laminar flow analysis in COMSOL, we first need to mold the flow channel design we have made (figure 7). Because COMSOL defines the entire flow channel as a wall.

When we add the flow channel itself, we can't get results because it can't establish the connection between the walls. The model simulated in this work was meshed by the built-in meshing module of COMSOL Multiphysics® and meshes with a tetrahedral automatically generated by the software.

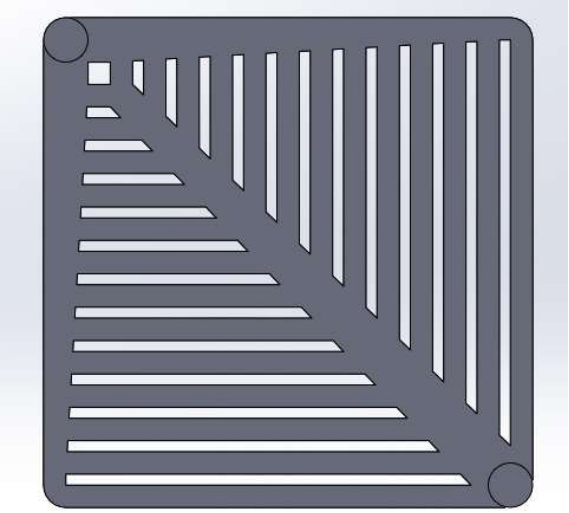

Figure 7. Mold extracted from biomimetic flow field design

Figure 8 shows the inlet and outlet of our analysis. Inlet input is entered in the upper right side of the design as in the leaves. The pointwise mass flux value we entered is 69.445 kg/(m^2*s). In the outlet part, it was thought that the pressure should be at the open-air pressure and the value of 101325 Pa was entered. The temperature of the water was taken as 20 degrees Celsius.

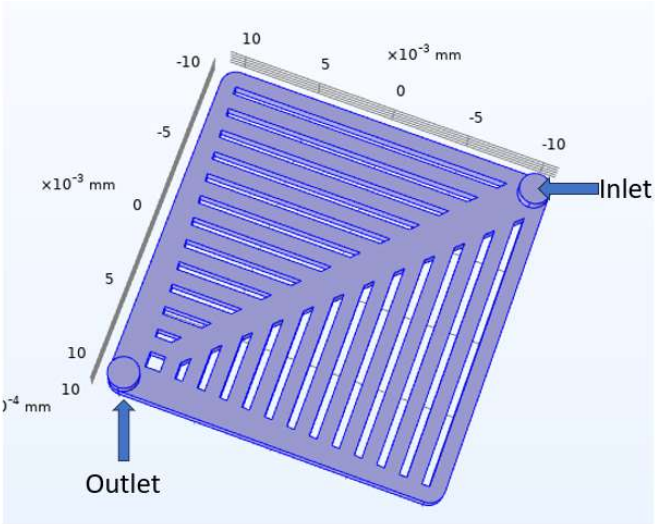

Figure 8. Laminar flow analysis

The obtained velocity analysis and pressure analysis results are provided in Fig. 9 and Fig. 10, respectively. The velocity was noted to have reached a maximum of 0.14 m/s, as seen in the numbers. The primary channel at the entry site often has a high water flow. There is a consistent slowing down of pace. Additionally, it began at 101325 Pa at the intake and descended steadily until it reached the pressure of zero pascal. This is done to better analyze the drop at a low-velocity value. This flow channel examination revealed no evidence of a danger to the middle membrane's integrity. Additionally, it is believed that the homogenous drop-in flow rate will help the growth of hydrogen by causing more water molecules to react. The experimental setup more clearly demonstrates this problem.

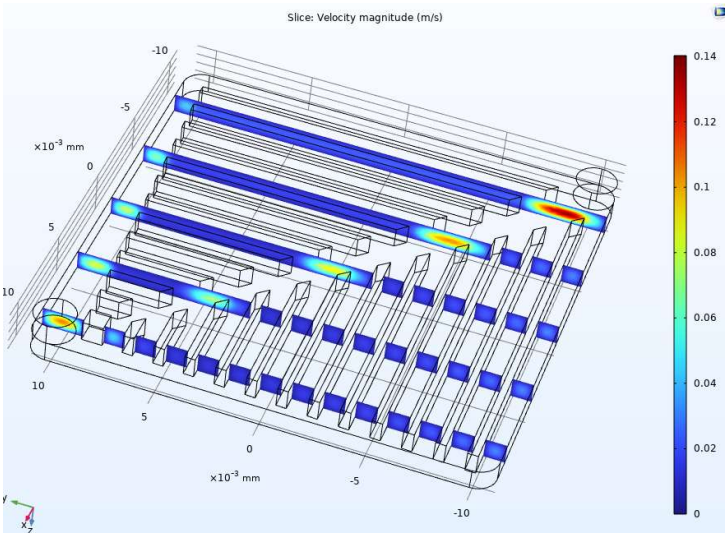

Figure 9. Velocity analysis result for biomimetic flow field

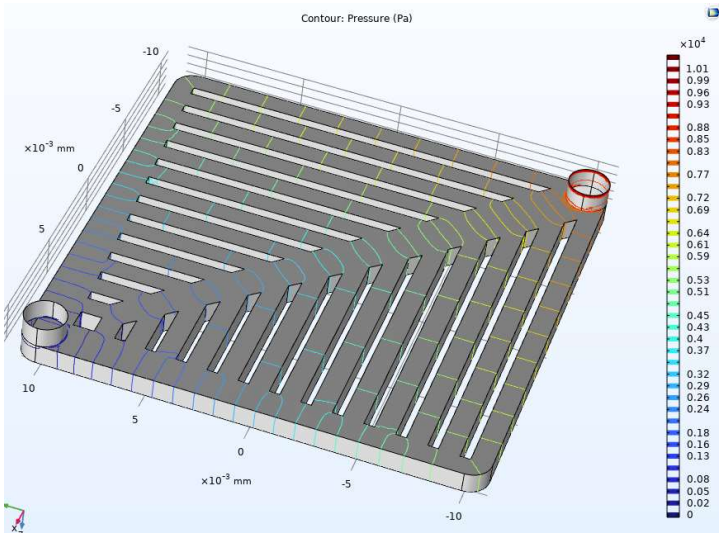

Figure 10. Pressure analysis result for biomimetic flow field

3.2. Analysis Results of the Serpentine Flow Channel

Figure 11 shows serpentine flow field design. For the serpentine flow field, utilized the same mass flow rate value as we used for the biomimetric flow field. The inlet and outlet of the mold are shown in Figure 12.

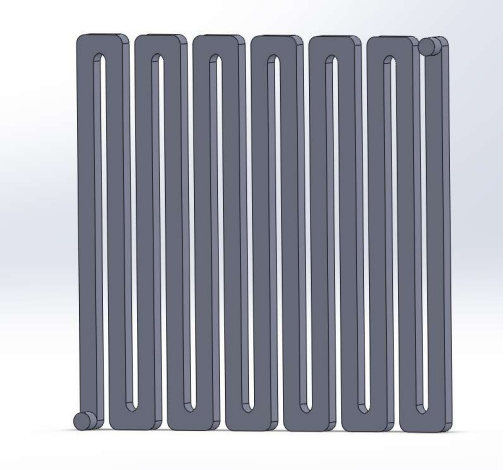

Figure 11. Mold extracted from serpentine flow field design

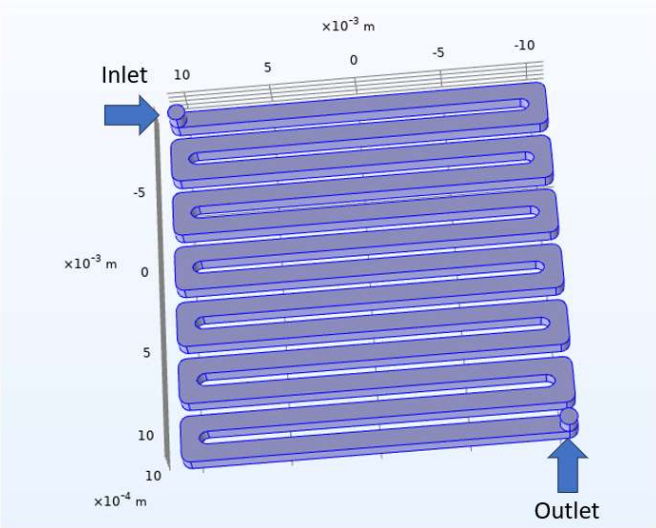

Figure 12. Laminar flow analysis for serpentine flow field

The obtained pressure analysis and velocity analysis results are provided in Fig. 13 and Fig. 14, respectively. The results of testing the flow channel with the serpentine flow channel showed that the lowest pressure was 3.43 pascals and the greatest pressure was 450 pascals. Furthermore, it was noted that the first two rows of the flow channels required some time for the pressure to be evenly distributed. Long-term injury and membrane piercing might result from this.

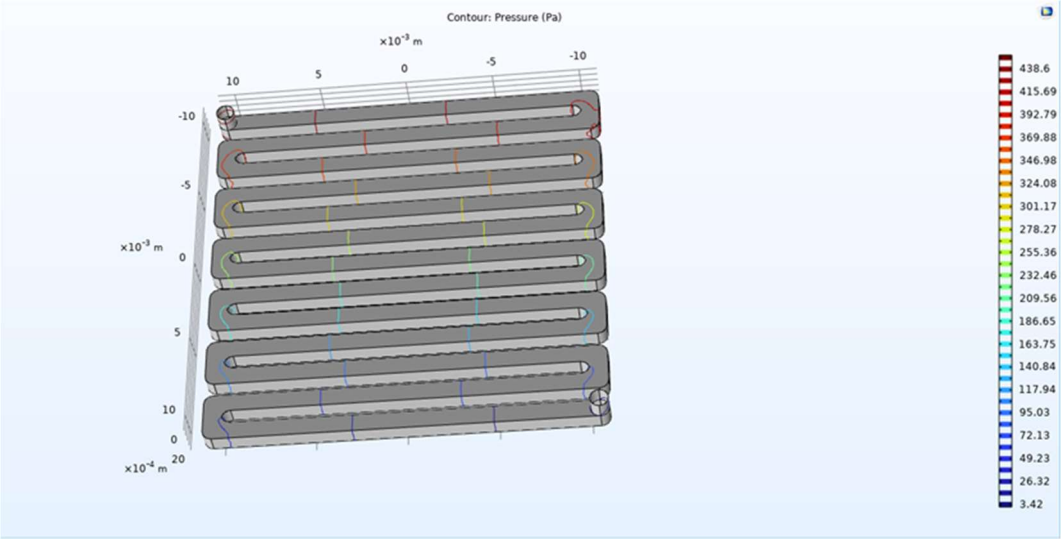

Figure 13. Pressure analysis result for serpentine flow field

In the same scenario as the velocity analysis, too rapid water movement in the flow channel may result in a drop in cell efficiency. It achieves its maximum speed in the channels, as seen in the diagram of the flow channels. The speed was found to be 0.01 m/s at the slowest location and 0.1 m/s at the fastest point.

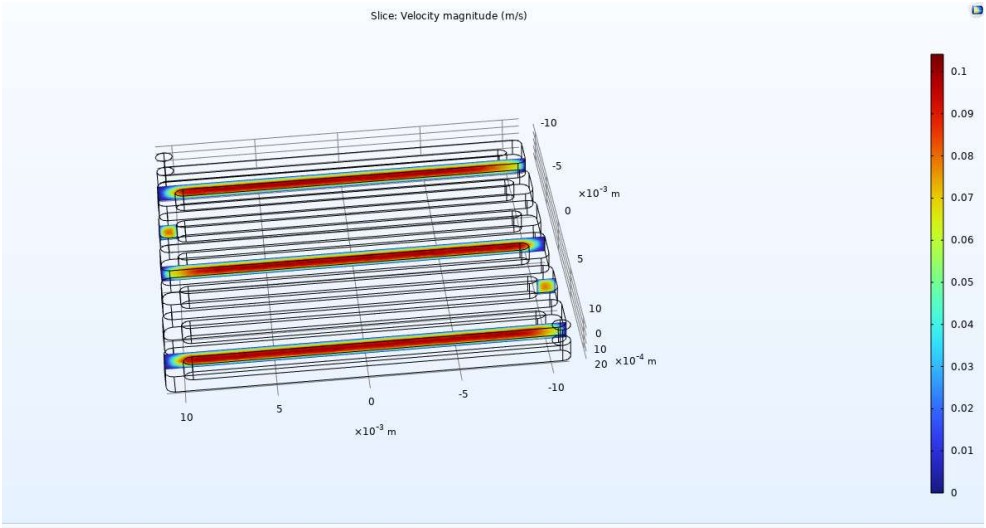

Figure 14. Velocity analysis result for serpentine flow field

3.3. Coating Results During MEA Preparation

The membrane is coated with ink by using a soft-tipped watercolor brush as a coating instrument. The first prepared membrane began to expand as cold ink was applied to it. The membrane's structure was entirely ruined after being allowed to dry for one day. In the second experiment, a

heating plate was positioned beneath the membrane to use the heat. It was also hoped to determine whether employing an unprepared membrane would make a difference. The membranes then underwent more deformation.

These outcomes made coating using the CCS technique unavoidable. Table 1 provides the weights before and after the application of the ink.

Table 1. Coating Process Data

Name of The Coated Electrodes	Weight before the coating (g)	Weight after the coating (g)	The total coated platin (g)
GDL Carbon 1	0.0912	0.1134	0.00222
GDL Carbon 2	0.0894	0.1094	0.002
Nickel Foam	0.6150	0.673	0.0058

3.4. Experimental Results For PEM Water Electrolyzer

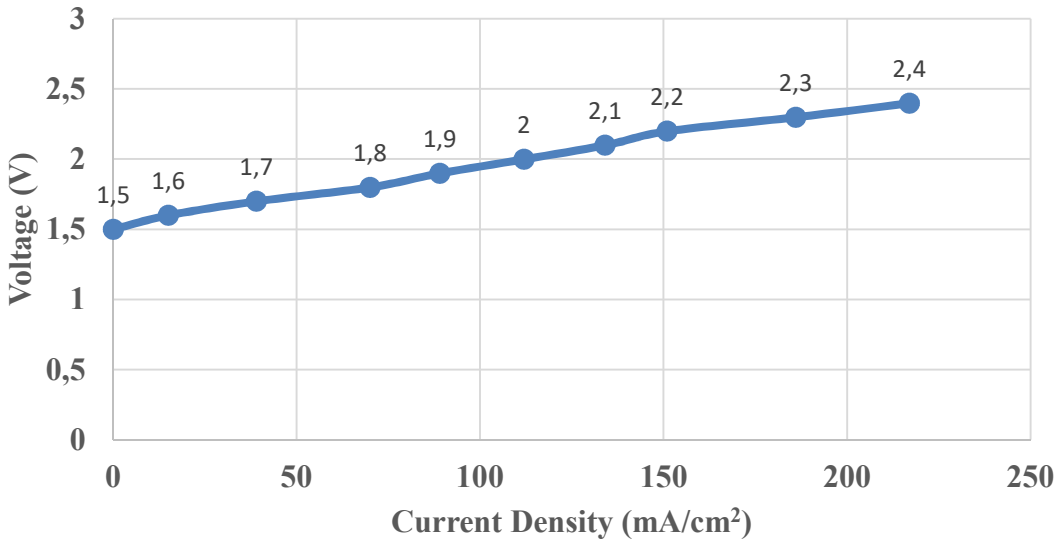

Figure 15. Polarization curve for two-side biomimetic flow field

In the context of hydrogen production and consumption, several calculations have been conducted. These calculations collectively elucidate the efficiency and energy dynamics within the hydrogen production and consumption process, specifically based on the values extracted at 2.1V from the aforementioned Table 2 of the Biomimetic Flow Field Design for PEM Electrolyzer.

Table 2. Efficiency Data from Biomimetic-Biomimetic Flow Field Design for PEM Electrolyzer

Voltage (V)	Ampere (A)	Time (Minutes)	Volume (ml)
2.1	0.81	1	5
2.1	0.82	3	20
2.1	0.82	5	35
2.1	0.83	7	40
2.1	0.83	9	50

Figure 16 presents the Polarization Curve for the Anode Side Serpentine - Cathode Side Biomimetic Flow Field in the context of the PEM electrolyzer. Furthermore, Table 3 provides *Efficiency Data from the same Anode Side Serpentine*- Cathode Side Biomimetic Flow Field Design for PEM Electrolyzer. These presented data have been instrumental in conducting efficiency calculations. The polarization curve in Figure 16 offers insights into the electrochemical behavior of the design, while the efficiency data in Table 3 allows for comprehensive efficiency assessment. Drawing from these datasets, efficiency calculations have been accurately carried out to provide a comprehensive understanding of the system's performance.

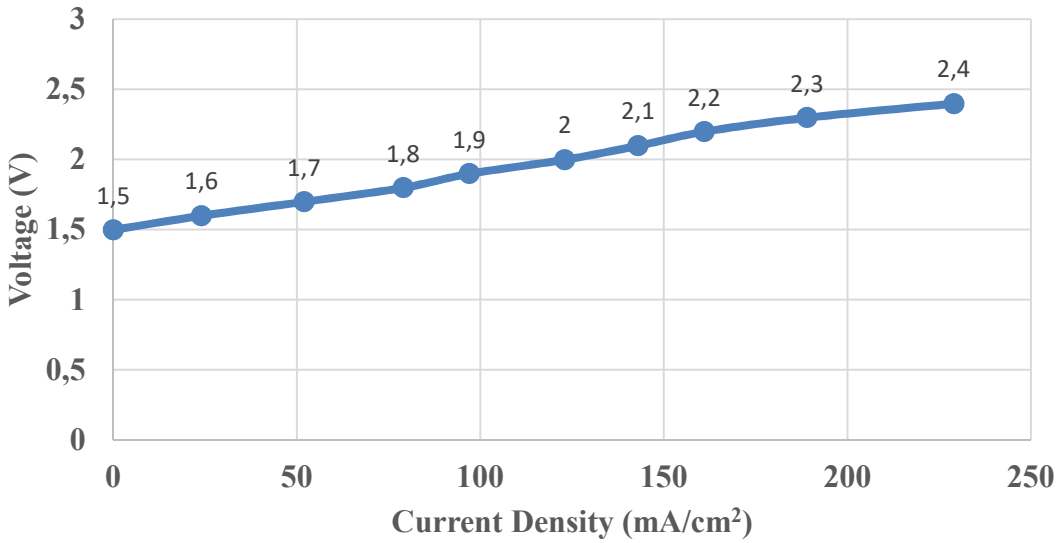

Figure 16. Polarization curve for anode side serpentine- cathode side biomimetic flow field

Table 3. Efficiency Data from Anod Side Serpentine – Cathode Side Biomimetic Flow Field Design for PEM Electrolyzer

Voltage (V)	Ampere (A)	Time (Minutes)	Volume (ml)
2.1	0.68	1	3
2.1	0.71	3	17
2.1	0.69	5	28
2.1	0.71	7	37
2.1	0.72	9	48

3.5. Experimental Results for Anion Exchange Membrane Water Electrolyzer

Figure 17 displays the Polarization Curve specifically associated with the Anion Exchange Membrane Water Electrolyzer (AEMWE), showcasing the performance under the Two-Side Biomimetic Flow Field configuration. Additionally, Efficiency Data from the Biomimetic-Biomimetic Flow Field Design for AEM Electrolyzer are provided in Table 4.

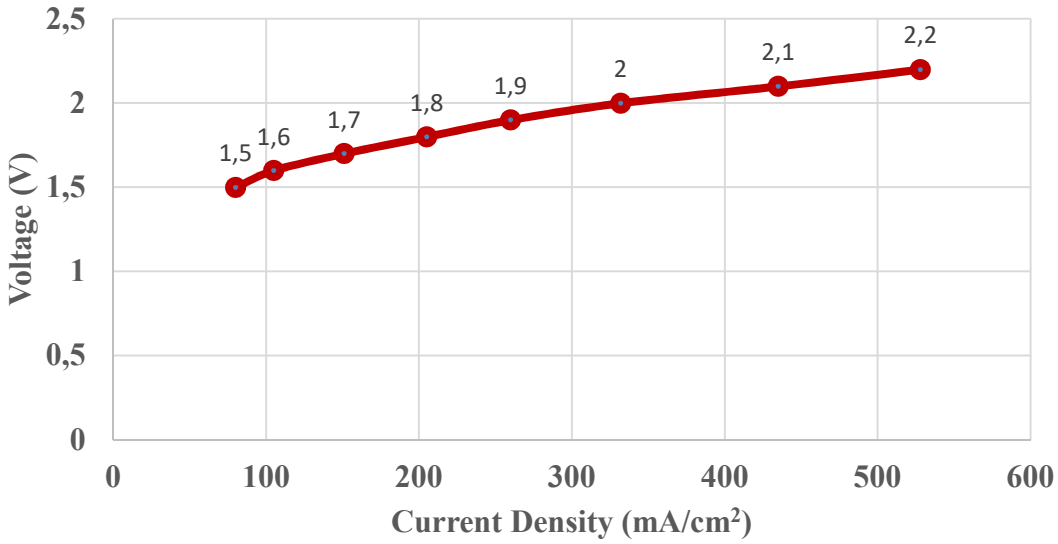

Figure 17. Polarization curve for two-side biomimetic flow field

Table 4. Efficiency Data from Biomimetic-Biomimetic Flow Field Design for AEM Electrolyzer

Voltage (V)	Ampere (A)	Time (Minutes)	Volume With Pump (ml)	Volume of Hydrogen (ml)
1.9	1.30	1	25	3
1.9	1.31	3	75	9
1.9	1.33	5	125	15
1.9	1.34	7	175	21
1.9	1.32	9	225	27

The peristaltic pump has a flow rate of 22 ml/min so, the flow rate of the pump has been removed from the calculation. Pure hydrogen output is shown in the table above.

3.6. Flow Field

As can be seen from the research conducted, although there is less current flowing through the flow channel, there has also been an increase in the quantity of hydrogen created. The Biomimetic-Biomimetic flow channel has attained a higher average current value of up to 2.1 volts in the same voltage range. The Serpentine-Biomimetic flow channel design produced greater average current levels after 2.1 volts. In addition, greater hydrogen production than with the PEM electrolyzer was noted. A successful flow channel with a low noble metal ratio that may be applied in this situation is one that was inspired by nature. Additionally, the trials' finding that it didn't harm the membrane demonstrated the ability of the flow channel to evenly disperse pressure.

3.7. About Anion Exchange Membrane Water Electrolyzer

As can be observed in the study, higher current density was achieved in the same voltage range. Despite the low use of the noble metal ratio, its performance in this way shows that this electrolysis method can go further. The amount of hydrogen output was low as expected, but the efficiency was also below the expected levels. This is thought to be due to the small amount of catalyst material used. In addition, the weakness of the coating method may also have affected the efficiency.

3.8. Future Work

Iron, manganese, nickel, etc. Cells with improved performance can be used for studies with catalysts made from inexpensive metals [1]. The impact of various flow channels on performance may be seen by experimenting with them. It is possible to investigate the gas diffusion layer, which

is unrelated to the subject of this study. Additionally, examining the functioning of the cell at various temperatures may be used to assess the effectiveness and performance of the cell.

4. CONCLUSION

In this study, it is experimentally observed that bioinspired flow channel design can help increase efficiency with selected electrolyzer technology with higher efficiencies at identical conditions. This may also enable use of less costly materials use and make the hydrogen generation more efficient and feasible in terms of cost. Further research is being designed to experimentally investigate use of different types of catalysts and modeling work for flow channel design for performance enhancement. Although the materials used in AEM cell contain fewer noble metals, it is noteworthy that it operates with an efficiency of 25% and the high current density of the cell in the polarization curve of the cell is noteworthy. It is thought that cell efficiency and performance can be increased by experimenting with different catalyst materials in the continuation of this study. It is thought that such studies will be supported more due to the increasing trend towards hydrogen technologies in today's world. If efforts are made, it is thought that the unit price of hydrogen production can be decreased.

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Abdullah Emre Avci: Conducted the experiments, analyzed the results, authored the research paper, and performed the analysis using COMSOL.

Mehmed Selim Cogenli: Supervised the experiments, wrote up the results, and addressed revisions.

Selahattin Celik: Served as the academic supervisor for the research and contributed to the literature review.

Hasan Ozcan: Acted as the academic supervisor for the analysis and served as the writing supervisor.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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