Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 6 (1), June 2017, pp 556-565
ISSN 2147-3471 © 2017

The surface area's effects of proton exchange membran and electrode on power generation in a hexagonal single chamber microbial fuel cell

E.Toklu[1], A.Coskun Avci[1,a], M.Yegin[2]

[1]Duzce University, Mechanical Engineering, Duzce, Turkey.
[2]Kocaeli University, Electrical Engineering, Kocaeli, Turkey.

Accepted 12 January 2017

Abstract
Microbial fuel cells (MFCs) have been used to produce electricity from different compounds, such as glucose, lactate and acetate. MFCs research has intensified in the past decade and the maximum MFCs power density output has been increased greatly and many types of waste streams have been tested by researchers. Power generation in microbial fuel cells is a function of surface areas of the proton exchange membran (PEM). The possibility of generating electricity with microbial fuel cells has been recognized, but practical applications have been slow to develop. To reduce capital and operational costs, simple and robust membrane-less MFCs reactors are desired, but these reactors require highly efficient biofilms. All currently available MFCs design are for experimental however, these designs are not ecenomic and sustainable. In this research, effect of proton exchange membrane and electrode surface areas on power generation is analyzed for a new design hexagonal chamber microbial fuel cell. Hexagonal chamber microbial fuel cell designed in this study has affordable, scalable, sustainable, high reliability features.

Keywords: Microbial fuel cells; wastewater treatment; power generation; PEM surface area

1. Introduction

Consumption of energy within the world has had a prosperous trend in the recent years [1]. Energy sources are classified into two form as non renewable and renewable sources [2]. Non renewable energy sources, which include an enormous portion of energy consumption, could be categorized into two major classifications as nuclear and fossil energy [3]. Fossil fuels negatively influence the nature owing to the emission of carbon dioxide. Consumption of fossil fuels has severely imperiled human life through its drastic aftermaths, such as global warming and atmospheric pollution [4].

As supplies of fossil fuels dwindle and concerns about continued contributions of additional carbon dioxide to the atmosphere intensify, there is an increasing need for new sources of energy from renewable carbon-neutral sources with minimal negative environmental impact [4, 5]. Producing electricity from organic matter with microbial fuel cells is a concept that arguably dates back almost 100 years [6]. A technology using microbial fuel cells (MFCs) that convert the energy stored in chemical bonds in organic compounds to electrical energy achieved through the catalytic reactions by microorganisms has generated considerable interests among academic researchers in recent years [6-7]. Microbial fuel cells (MFC) works similarly to a voltaic cell, except they use the catalytic reaction of microorganisms such as bacteria to convert virtually any organic material into electricity [8]. Microbial fuel cells have been used to produce electricity from different compounds, including acetate, lactate, and glucose [9]. In an MFC, microorganisms degrade organic matter, producing electrons that travel through a series of respiratory enzymes in the cell resulting in energy for the cell in the form Adenosine triphosphate. The electrons are then released to a terminal electron acceptor which accepts the electrons and becomes reduced [9-11].

MFC is an emerging technology that uses biofilms as catalysts to convert chemical energy in organic (and some inorganic) matter directly into electricity [12]. MFC has adistinct advantage in that it can utilize low-grade biomass or even wastewater, which is

[a] Corresponding author;
Phone: +90-507-338-5915, Email:arzucoskun@duzce.edu.tr

otherwise not utilized, to produce bioelectricity. Tremendous advances have been made in the past decade [12-14]. Research activities and the number of publications in this area have exploded in recent years. Although MFCs have an attractive potential for alternative green energy production, major technical hurdles remain for their practical deployment [12].

A typical MFC is a dual-chamber MFC consisting of an anodic chamber and a cathodic chamber separated by a proton exchange membrane (PEM). In the anodic chamber, an anaerobic biofilm oxidizes a substrate, producing electrons and protons [12,14-18]. The protons are conducted to the cathode chamber through the PEM, and the electrons flow through an external circuit from the anode to the cathode and in the process drive an external load [16,20]. Protons and electrons are reacted in the cathode chamber along with parallel reductionof oxygen to water [16,21]. It is worth mentioning that active biocatalyst in the anode compartment oxidizes the carbon sources or substrates, and generates electrons and protons. Oxygen in the anode chamber will inhibit the production of electricity [16,22].

Typical electrode reactions are shown below using acetate as an example substrate [14]:

Anodic Reaction:

$$CH_3COO^- + 2H2O \longrightarrow 2CO_2 + 7H^+ + 8e^-$$

Cathodic Reaction:

$$0_2 + 4e^- + 4H^+ \longrightarrow 2H_2O$$

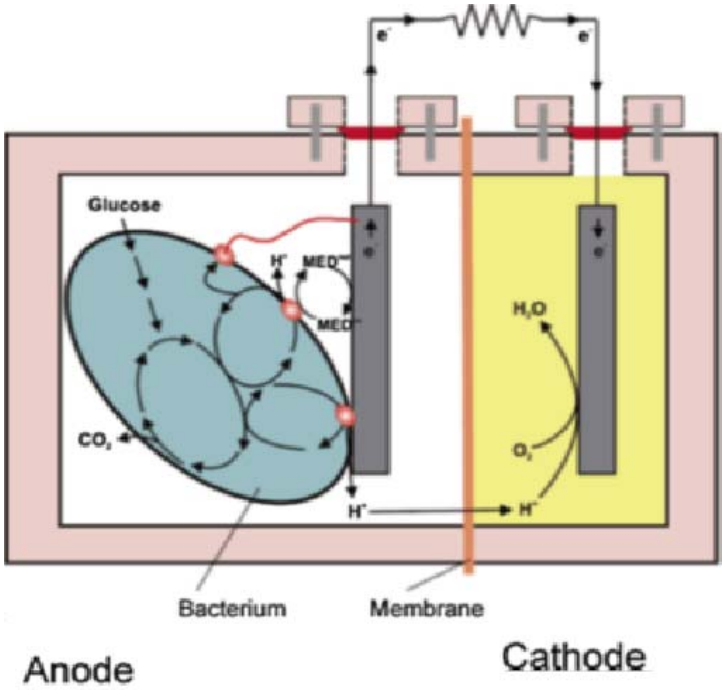

Figure 1. The MFC system is consisted of anode and cathode compartments [23].

2. Types of a microbial fuel cells

2.1. Two chambered microbial fuel cells

Two chambered fuel cells as the name suggests are composed of two compartments or chambers. Both the cathode and anode are housed in different compartments connected via a proton exchange membrane or sometimes salt bridge to allow protons to move across to the cathode while blocking the diffusion of oxygen into the anode (24). Two-chambered MFCs are typically run in batch mode often with a chemically defined medium such as glucose or acetate solution to generate energy [14].

PEMs or salt bridges mainly function as a medium for transfer of protons to make the circuit or reaction process complete as discussed earlier but also prevent the anode to come in direct contact with oxygen or any other oxidizers [25]. The compartments can take various practical shapes. The schematic diagram of two-compartment MFCs are shown in Figure 2. It can be suitably designed to scale up to treat large volumes of wastewater and other source of carbon [24-25].

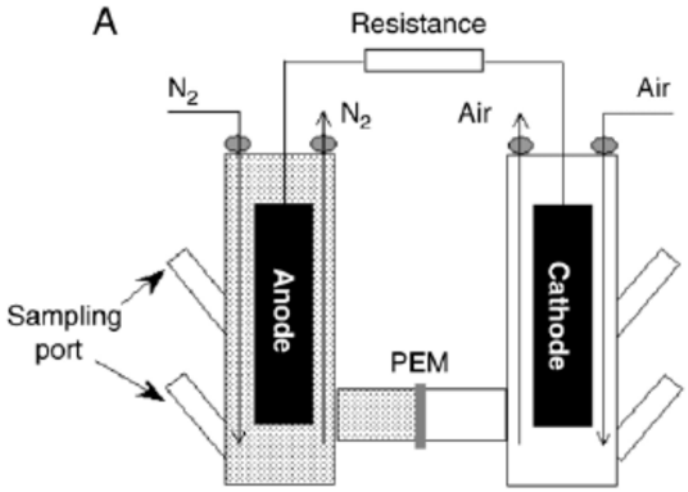

Figure 2. Schematic diagram of a typical two-chamber microbial fuel cell [14].

2.2. Single chambered microbial fuel cells

Single Chambered fuel cells consist of only one compartment - an anode compartment. They typically possess only an anodic chamber without the requirement of aeration in a cathodic chamber [14]. There is no definitive cathode compartment and they may or may not contain a PEM. Porous cathodes form one side of the wall of the chamber and can utilise oxygen from the atmosphere allowing protons to diffuse through them. The anodes are normal carbon electrodes but the cathodes are either porous carbon electrodes or PEM bonded with flexible carbon cloth electrodes [24-25]. It is designed an onecompartment MFC consisting of an anode in a rectangular anode chamber coupled with a porous air- cathode that is exposed directly to the air as shown in Figure 3.

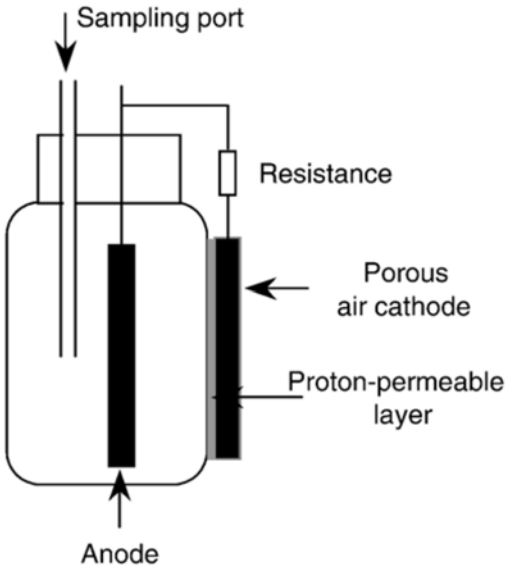

Figure 3.Schematic diagram of a typical a rectangular anode chamber microbial fuel cell [14].

Another type of Single Chambered Fuel Cells reactor is housed both the anode and the cathode in one chamber. It consisted of a single cylindrical Plexiglas chamber with eight graphite rods (anode) in a concentric arrangement surrounding a single cathode as shown in Figure 4; carbon/platinum catalyst/proton exchange membrane layer was fused to a plastic support tube to form the air-porous cathode in the center. Protons are transferred from the anolyte solution to the porous air-cathode designed an MFC consisting of an anode placed inside a plastic cylindrical chamber and a cathode placed outside [2,11].

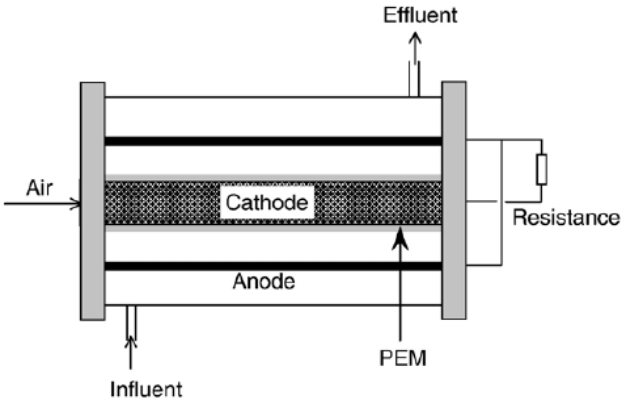

Figure 4. Schematic diagram of a typical a cylindrical single-chamber microbial fuel cell [11].

2.3. Stacked microbial fuel cells

These are another type of construction in which fuel cells are stacked to increase voltage. This type of construction doesn't affect each cell's individual Coulombic efficiency but together it increases the output of the overall fuel cell to be comparable to normal power sources. Coulombic efficiency describes how much of the electrons can be abstracted from the electron-rich substrates via the electrodes [14]. They can be either stacked in series or stacked parallel. Both have their own importance and are high in power efficiency and can be practically utilized as power source. It is not a measurement of electron transfer rate, while the authors described how much substrate was used for electricity generation before the stream flowed out of the MFCs or MFC stacks differed greatly in the two arrangements with the parallel connection giving about an efficiency six times higher when both the series were operated at the same volumetric flow rate. The parallel-connected stack has higher short circuit current than the series connected stack. This is due to the higher short circuit current and thus higher maximum bioelectrochemical reaction rate allowed in the connection of MFCs in parallel compared to those in series [26-28].

A stacked MFC is shown in Fig. 9 for the investigation of performances of several MFCs connected in series and in parallel. Enhanced voltage or current output can be achieved by connecting several MFCs in series or in parallel.

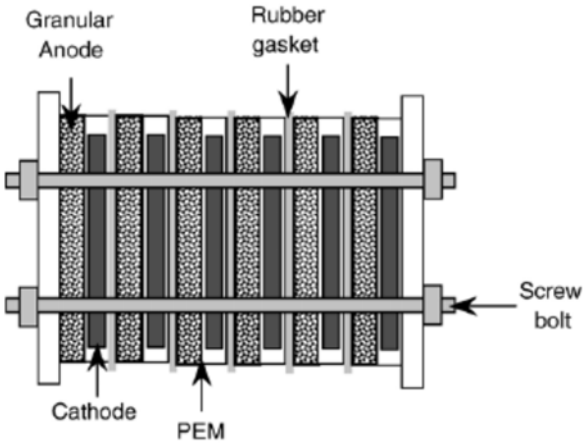

Figure 5. Schematic diagram of a typical a stacked single-chamber microbial fuel cell [14].

3. Components of a microbial fuel cell

3.1. Anodes

The requirements of an anode material are; highly conductive, non-corrosive, biocompatible, high surface area, inexpensive and scaled up to larger sizes [26]. The simplest and most versatile material

for an anode is carbon: relatively inexpensive, easy to handle, has a defined surface area and is available in a wide range of forms such as compact plates, rods, granules, as fibrous material and as glassy carbon [26,30]. Metal anodes consisting of noncorrosive stainless steel mesh can be utilized, but copper is not useful due to the toxicity of even trace copper ions to bacteria [8].

3.2. Cathodes

The choice of the cathode material greatly affects the overall performance of the MFC; as such great care is taken when choosing its material which varies based on whatever its application [36]. The same materials listed for anodes previously are also used for cathodes [26]. Oxygen is the most obvious choice of electron acceptor for an MFC due to its high oxidation potential, availability, low cost (free), sustainability, and the lack of a chemical waste product (water being the only end product). A tri-phase reaction (solid catalyst, air and water) occurs at air-breathing cathodes as electrodes. Pt catalysts are usually used for dissolved oxygen to increase the rate of oxygen reduction [37]. The electrons, protons and oxygen must all meet at the catalyst. The catalyst must be exposed to both water and air and must have a conductive surface so that the protons and electrons in these different phases can reach the same point [26]. The most common commercialcathode material is carbon paper pre loaded with a Pt catalyst on one side.

3.3. Membrane

In MFCs a membrane is not necessarily needed as the protons can be conducted by water. They are only used in MFCs, with the exception of sediment MFCs and single compartment as a means to keep the anode and cathode liquids separate and as a barrier to other species in the cell while allowing protons produced at the anode to migrate to the cathode. Unfortunately MFC membranes are expensive and decrease overall system performance by increasing internal resistance [26,31].

3.4. Medium / Substrate

One of the first decisions an MFC researcher will have to make is the choice of bacterial inoculum and medium. Wastewater treatment plants contain such a rich and diverse supply bacteria, so it is preffered [26]. Synthetic or chemical wastewater with well-defined composition is used by several researchers as it is easy to control in terms of loading strength, pH and conductivity [36]. In MFCs, substrate is regarded as one of the most important biological factors affecting electricity generation. The substrate influences integral composition of the bacterial community in the anode biofilm and the MFC performance including the power density and Coulombic efficiency [35].

4. Performance of a microbial fuel cell

4.1. Chemical oxygen demand

Chemical Oxygen Demand (COD) removal from wastewater reflects the total energy harvested from the organic matters. The COD removal efficiency (η_{COD}) is calculated from the equation [12];

$$\eta_{COD} = (COD_{inf} - COD_{eff}) / COD_{inf} \times 100\ \%$$

where;
COD_{inf} : Influent COD (mgL^{-1})
COD_{eff} : Effluent COD (mgL^{-1})

4.2. The Actual closed circuit potential output:

The actual closed circuit potential output of an MFC is much less than the theoretical open circuit potential. The actual closed circuit potential is calculated from standard potentials as[12];

$$U_{output} = E_{cathode} - E_{anode} - \Sigma\eta_J + I.R_i$$

Where
η_j: The sum of activation and concentration overpotentials for the anode and cathode
R_i: The internal resistance
I: The current flow
$E_{cathode}$: Cathode potentials
E_{anode} : Anode potentials
The electrode potentials are calculated based on the Nernst equation.

4.3. Coulombic Efficiency:

Coulombic efficiency reflects the ratio of the number of electrons passing through the external load R (ohms), which generates electricity, to the number of electrons removed from the substrate during bioconversion. It is calculated from the equation below for batch MFC operation with an air cathode [24];

$$CE = \frac{(\int_{t1}^{t2} Udt)/R}{F.b.(\Delta COD).V}.MW$$

where;

U: The output voltage as function of time (volt)
R: The external load (ohm)
F: Faraday's constant
b: The number of electrons exchanged per mole of O_2
ΔCOD: The removal of COD
V: The wastewater volume in the anodic chamber (L)
MW: The molecular weight of O2.

5. Power Density

MFC power density output based on an electrode surface area (P_A) and power density based on the liquid volume in the anodic chamber or the cathodic chamber (P_v) are readily calculated from the equations [12];

$$P = I.U$$

$$P_A = P / A_{electrode}$$

$$Pv = P / V_{liquid}$$

where;
$A_{electrode}$: The surface area of an electrode
V_{liquid}: The liquid volume in the anodic or the cathodic chamber.

It is developed an equation to model power output as a function of electrode and PEM surface areas to demonstrate that the power output is predictable from any combination of them. It is observed that power output is most strongly correlated to PEM size. The maximum power output P (mW) is found to be well described by [37];

$$P = \frac{A_{PEM}}{10000} \text{ x } \frac{126.6 \text{ x } (\frac{A_{CAT}}{A_{PEM}})^{0,439}}{1 + [0.155 \text{ x } \frac{A_{PEM}}{A_{AN}}]^{2,45}}$$

where;
A_{PEM}: The surface area of PEM
A_{CAT}: The surface area of cathode
A_{AN}: The surface area of anode

6. MFC setup

6.1. Design criteria

All currently available MFC designs are for experimental however, these designs are not ecenomic and sustainable. Hexagonal chamber microbial fuel cell designed in this study has affordable, scalable, sustainable, high reliability features. Designed hexagonal microbial fuel cell are shown in Interior views and schematic design of a hexagonal chamber microbial fuel cell are shown is Figures 8-10.

The design consists of a variable number of identical hexagonal geometry module. In addition, these modules are located in a frame that will allow the flow of waste water and fresh air. The anode electrode located in each module consists of fibrous carbon distributed randomly shape in volume. The lateral walls of the module is completely coated with PEM. Lateral walls, is composed of three layers to support structurally to PEM. The inner and outer layers are a grid pattern which has small radius stainless steel wire (colum) with high elasticity modulus. Colums are placed in vertical direction on outer edges with an angle of 120 degrees to provide structural support to the lateral surface. There are also six bar cylindrical columns to show resistance to compression and tension stress between the ceiling and floor.

The top and bottom of the module, columns extending along the outer edges and inner columns are manufactured from stainless steel. Outer portions of the lateral surfaces are coated with a porous cathode electrode composed of carbon cloth. Waste water inlet is located at the bottom and waste water outlet and anode terminal are located at the top. The gap between them 10 mm, respectively and the modules are placed in the frame. Frame has a closed outer surface and fresh air flow will be provided with low speed and high flow rate fan in frame perpendicular to the water flow. The exhaust duct is located opposite of the fan.

Waste water inlet are connected to a collector with a separate tubing. The collector is supplied with buffer waste water tank. The anode and cathode terminals will be connected to a power supply with separate cable. Power conversion is made with buck and boost converters accordance with the voltage/current ratio required from the power unit. Hexagonal chamber MFC ve single chamber MFC design criterias are shown in table 1 below. The interior and exterior view of single chamber MFC is also shown in Figure 6 and 7.

Table 1. Design criterias of hexagonal chamber and single chamber MFC design

	Hexagonal Chamber MFC Design Analysis	Single Chamber MFC Design Analysis
Lengh of Chamber (mm)	400	400
Surface Area of Anode (m^2)	-	$7{,}728.10^{-3}$
Surface Area of Cathode (m^2)	0,12	0,032
Surface Area of PEM (m^2)	3,96	$5{,}591.10^{-3}$
Volume of Chamber (L)	469,7	1327
Ratio of PEM surface Area to Volume of Total Wastewater (m^{-1})	8.431	5.79

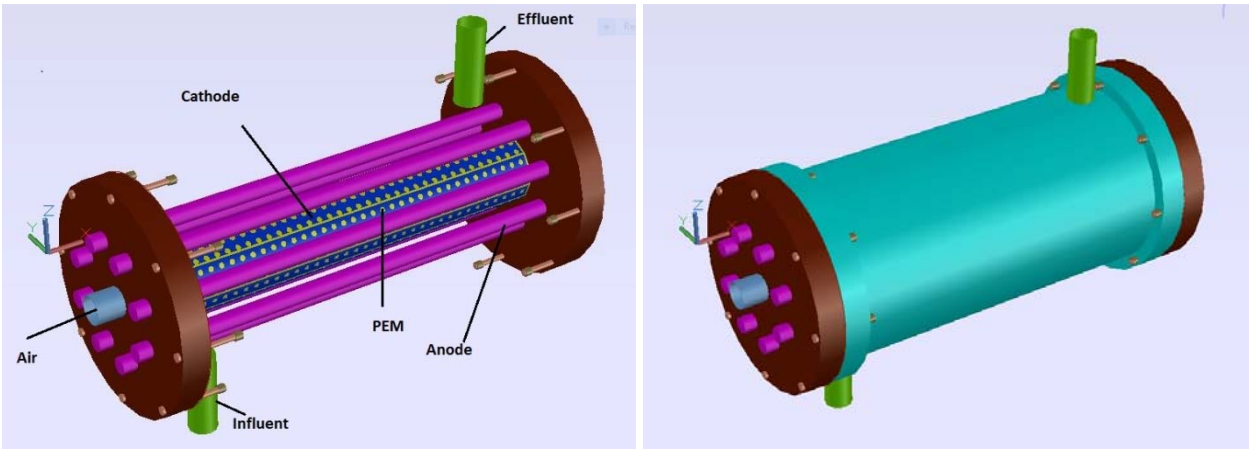

Figure 6-7. The inside and the exterior view of single chamber microbial fuel cell.

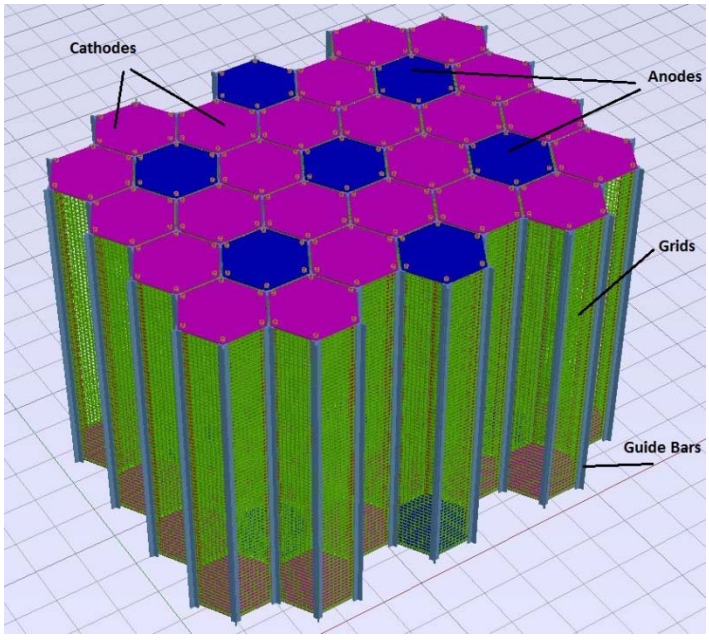

Figure 8. Schematic design of a hexagonal chamber microbial fuel cell.

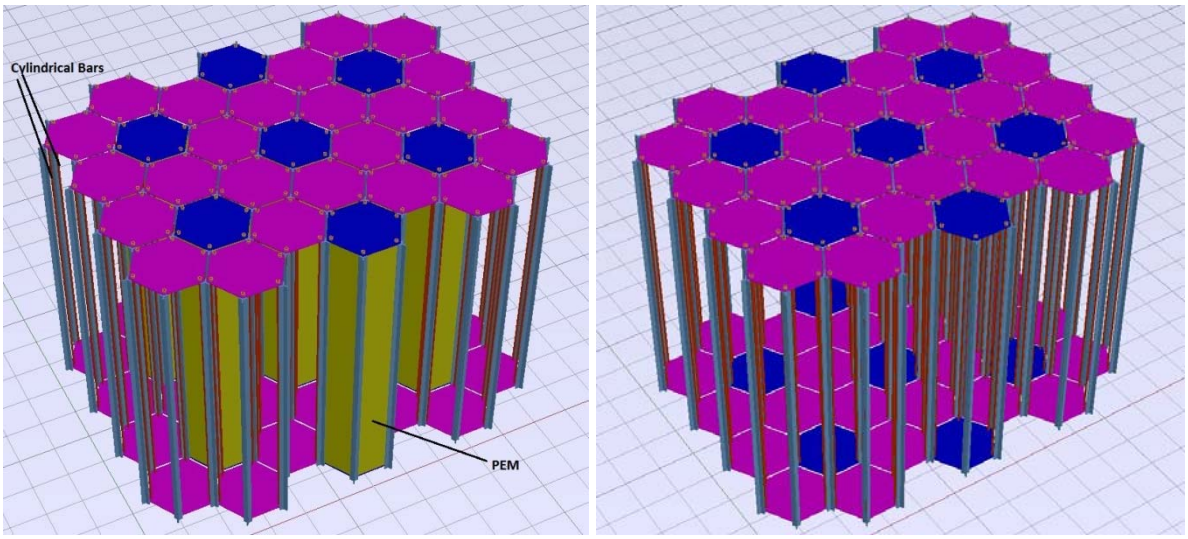

Figure 9 - 10. The view of guides and bars for hexagonal chamber microbial fuel cell.

6.2. Design Properties

Properties of hexagonal chamber microbial fuel cell are below:

a) High Reliability:

a.On Service Refuling: Modules can be added or removed while the system continues to function. Instead of the removed modules, fake modules can be arranged in identical geometry.

b.System maintenance can be planned in parts. Thus, the system can operate continuously.

c.Flow distribution is managed by collectors.

b)Sustainability: Toxic effects affect some modules earlier so collective bacteria loss can be prevented by following the module power.

c)Scalability: Each unit can be scaled depending on the frame itself. In addition, a large amount of scaling can be done by establishing parallel units. Scaling cost is lower than other MFC designs. Hexagonal MFC is a scalable design. Single chamber MFC is designed for experimental purposes so effective scaling is dfficult.

d) Economical: All components except PEM of the system are products available on the market at low prices. PEM is the most expensive material in all components so effective using of PEM is based on the geometrical design of the system.

e)Using fibrous carbon as the anode material will provide extreme anode surface area and bacteries can hold and distributed on the surface. In other designs, the anode surface area is too small, there is no surface area can hold bacteria.

6.3. Analysis and Calculations

Maximum power output is calculated 1,5738 mW for single chamber microbial fuel cell using table 1. Area of anode for equivalent maximum power calculated 0,11 m2 for hexagonal chamber microbial fuel cell. Surface area of anode versus maximum power output is shown in figure 11.

7. Conclusion

When comparing the design, hexagonal chamber and single chamber height are equal in this study. Anode electrode located in each module consists of fibrous carbon distributed randomly shape in volume in hexagonal MFC. Catode of hexagonal MFC is calculated 3,75 times of single chamber MFC when length of chambers are same. If hexagonal chamber MFC and single chamber MFC have same volume, catode of hexagonal MFC is calculated approximately 11,5 times of single chamber MFC. Utilization ratio of PEM is important to calculate maximum power and cost. In this study, utilization of PEM for hexagonal MFC is calculated 1,5 times of single chamber MFC. 1 LT waste water interacts with more PEM. PEM cost is important for all MFC design so it is shown that hexagonal chamber MFC is

more economical and more efficient.

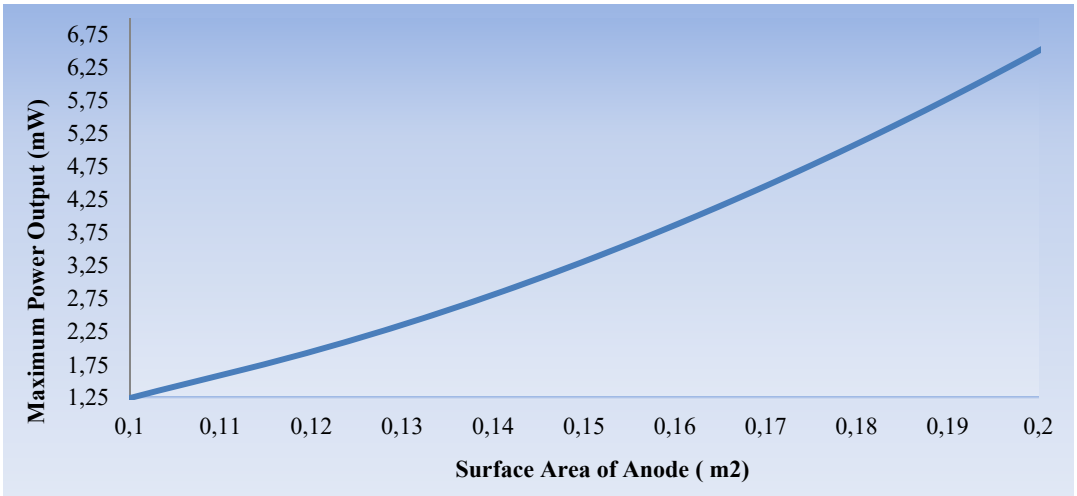

Figure 11. Surface area of anode vs.maximum power output.

References

[1] Rahimnejad M, Ghoreyshi A, Najafpour G, Power generation from organic substrate in batch and continuous flow microbial fuel cell operations. Appl Energy 2011; 88: 3999–4004.

[2] Güllü D, Atila Cağlar A, Akdeniz A, Recent energy investigations on fossil and alternative nonfossil resources in Turkey. Energy Conversion and Management 2002; 43:575–589.

[3] Rahimnejad M, Mokhtarian N, Najafpour G, Ghoreyshi A, Dahud W, Effective parameters on performance of microbial fuel cell, IEEE; 2009: 411–415.

[4] Rahimnejad M, Ghoreyshi G, Najafpour G, Younesi H, Shakeri M, A novel microbial fuel cell stack for continuous production of clean energy. International Journal Hydrogen Energy 2012; 37:5992–6000.

[5] Lovley D, Microbial fuel cells: novel microbial physiologies and engineering approaches. Energy Biotechnology 2006; 17:327–332

[6] Shukla A, Suresh P, Berchmans S, Rahjendran A: Biological fuel cells and their applications. Curr Sci 2004; 87:455-468.

[7] Allen RM, Bennetto HP, Microbial fuel-cells: electricity production from carbohydrates. Appl Biochem Biotechnol 1993; 39/ 40:27–40.

[8] Wastewater Treatment And Electrıcıty Generatıon Usıng Mıcrobıal Fuel Cells ; March 2012, Thesis Submitted As Part Of The Assessment For The Award Of B.Sc. (Honours) Environmental Science.

[9] L i u H, R a m a n a t h a n R, L o g a n B, Production of Electricity during Wastewater Treatment Using a Single Chamber Microbial Fuel Cell; Envıronmental Scıence & Technology 2004; 38.

[10] Logan B, Microbial Fuel Cells, New Jersey, Wiley-Interscıence John Wiley and Brown TL, Lemay HE, Bursten BE, Murphy CJ, Woodward P, Chemistry, the central science, eleventh edition, New Jersey, Pearson Education Inc 2011; 851-859.

[11] Liu H, Ramnarayanan R, Logan BE. Production of electricity duringwastewater treatment using a single chamber microbial fuel cell.Environ Sci Technol 2004; 28:2281–5.

[12] Minghua Z, Hongyu W, Daniel J, Ingyue G, Recent advances in microbial fuel cells (MFCs) and microbial electrolysis cells (MECs) for wastewater treatment, Bioenergy and Bioproducts. Chem Technol Biotechnol 2013; 88: 508–518.

[13] Logan BE and Regan JM, Microbial fuel cells - challenges and applications. Environ Sci Technol 2006; 40:5172–5180.

[14] Du Z, Li H and Gu T, A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. Biotechnol Adv 2007; 25:464–482.

[15] Rabaey K, Boon N, Hofte M and Verstraete W, Microbial phenazine production enhances electron transfer in biofuel cells. Environ Sci Technol 2005; 39:3401–3408.

[16] Rahimnejad M, Adhami A, Darvari S, Zirepour A, Oh S, Microbial fuel cell as new technology for bioelectricity generation: A review. Alexandria Engineering Journal 2015; 54: 745–756.

[17] Ghasemi M, Wan WR, Ismail WR, Rahimnejad M, Ismail A, Leong JX, Miskan M, Ben Liew K, Effect of pretreatment and biofouling of proton exchange membrane on microbial fuel cell performance. Int. J. Hydrogen Energy 2012; 38:5480–5484.

[18] Wilkinson S. "Gastrobots" — benefits and challenges of microbial fuel cells in food powered robot applications. Auton Robot 2000; 9:99−111.

[19] Antonopoulou G, Stamatelatou K, Bebelis S, Lyberatos G, Electricity generation from synthetic substrates and cheese whey using a two chamber microbial fuel cell. Biochem. Eng. J 2010; 50:10–15.

[20] Rahimnejad M, Najafpour G, Ghoreyshi A, Effect of mass transfer on performance of microbial fuel cell. Intech 2011; 5: 233–250.

[21] Sharma Y, Li B, The variation of power generation with organic substrates in single-chamber microbial fuel cells (SCMFCs). Bioresource. Technol 2010; 101:1844–1850.

[22] Najafpour G, Rahimnejad M, Ghoreshi A, The enhancement of a microbial fuel cell for electrical output using mediators and oxidizing agents. Energy Sourc 2011; 33:2239–2248.

[23] Logan BE, Hamelers B, Rozendal R, Schro¨ der U, Keller J, Freguia S, Aelterman P, Verstraete W, Rabaey K, Microbial fuel cells: methodolog.

[24] Liu H, Logan BE. Electricity generation using an air-cathode single chamber microbial fuel cell in the presence and absence of a proton exchange membrane. Environ Sci Technol 2004;38: 4040–6.

[25] Rabaey K, Verstraete W. Microbial fuel cells: novel biotechnology for energy generation. Trends Biotechnol 2005;23:291–8.

[26] B.E. Logan, Microbial Fuel Cells, New Jersey, Wiley –Interscience John Wiley and Sons, Inc. (2008).

[27] Ieropoulos I, Greenman J, Melhuish C, Hart J, Energy Accumulation and Improved Performance in Microbial Fuel Cells Power Sources. Power Sources 2005;, 145:253-256.

[28] Karmakar S, Kundu K, Kundu S, Design and development of microbial fuel cells, Appl Microbial Biotechnol 2010: 1029-1034.

[29] Aelterman P, Rabaey K, Pham K, Boon N, Verstraete W, Continuous electricity generation at high voltages and currents using stacked microbial fuel cells, Environ Sci Technol 2006; 40: 3388–3394.

[30] Gil G, Chang I, Kim B, Kim M, Jang J.K, Park H.S, Kim H.J, Operational parameters affecting the performance of a mediator-less microbial fuel cell, Biosens. Bioelectron 2003; 18:327-334.

[31] Reimers CE, Tender LM, Fertig S, Wang W, Harvesting energy from the marine sediment-water interface phthalocyanine and CoTMPP based oxygen reduction catalysts as cathode materials in microbial fuel cells, Environ.Sci. Technol 2001; 35:192-195.

[32] Cheng S, Liu H, Logan BE, Power densities using differentcathode catalysts (Pt and CoTMPP) and polymer binders (Nafion and PTFE) in single chamber microbial fuel cells, Environ. Sci.Technol 2006; 40:364-369.

[33] Zhao F, Harnisch F,Schro¨der U, Scholz F, Bogdanoff P, Herrmann I, Application of pyrolysed iron(II) phthalocyanine and CoTMPP based oxygen reduction catalysts as cathode materials in microbial fuel cells, Electrochem. Commun 2005; 7:1405-1410.

[34] Angenent LA, Wrenn BA, Optimizing mixed-culture bioprocessing to convert wastes into bioenergy. Bioenergy 2008: 179–194.

[35] Chae K, Choi M, Lee J, Kim J, Kim I, Effect of different substrates on the performance, bacterial diversity, and bacterial viability in microbial fuel cells, Biores. Technol 2009; 100: 3518–3525.

[36] Venkata Mohan S, Mohanakrishna G, Velvizhi G, Lalit Babu V, Sarma P, Biocatalyzed electrochemical treatment of real field dairy wastewater with simultaneous power generation, Biochemical Engineering Journal 2010; 51: 32-39.

[37] Sang-Eun Oh S.E, Logan B, Proton exchange membrane and electrode surface areas as factors that affect power generation in microbial fuel cells, Applied Microbiol Biotechnoly 2006; 70: 162–169.