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Mass Transfer Limitation in Different Anode Electrode Surface Areas on the Performance of Dual Chamber Microbial Fuel Cell

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ABSTRACT

In this study, the effect of different electrode surface areas on the performance of dual chamber Microbial Fuel Cells (MFC) was investigated. Four different electrodes with 12, 16, 20 and 24 cm^2 surface areas were tested in an MFC system. The 20 cm^2 electrode generated an output power of 76.5 mW/m^2 was found to be the highest among all the electrodes tested. This might be due to better interactions with microorganism and less mass transfer limitation. In addition, this indicates that the chances for attachment of bacteria and generation of electricity in larger electrode surface areas might be limited by mass transport and by higher surface area. The output power generation was then followed by the 16, 12 and 24 cm^2 electrodes which generated 69.6, 64.7 and 61.25 mW/m^2 electricity, respectively.

Keywords: Electrode Surface Area, Microbial Fuel Cells, Power Generation, Anode, Mass Transfer

1. INTRODUCTION

Nowadays, there are lots of concerns raised due to the exponential increase in the worldwide energy demand whereas the conventional energy sources (mostly fossil fuels) are depleted. Besides that, as reported by Wen *et al*. (2009), the combustion of fossil fuels has several negative effects on the environment such as CO_2 emissions, elevation of earth temperature, climate change. Therefore, introducing renewable sources of green energy is becoming more and more interesting among researchers. Amini *et al*. (2010) and Heidari *et al*. (2009) proposed that wastewater organic materials offer a promising alternative energy source. Microbial Fuel Cells (MFC) are a type of fuel cell that converts chemical energy to electrical energy through the action of microorganism as biocatalysts as described by Lovley (2006). Several other factors affect the performance of MFCs such as electrode spacing, electrode materials, catalysts, microbial inoculums, proton exchange membranes, surface area. The biocatalysts used in MFCs are more advantageous than the other parameters of microbial fuel cells due to their biocompatibility and high efficiency.

The attractiveness of MFCs comes from simultaneous wastewater treatment and the production of energy. For electricity production, Ghasemi *et al*. (2011) have suggested that a soluble electron donor such as neutral red methyl blue, thionine should be oxidized by

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microorganisms in the anode compartment to produce electrons and protons. The electrons produced by the bacteria can be transferred to the anode by electron mediators as shown by Kim *et al*. (2002). In essence, Logan *et al*. (2005) proposed that the generation of current is the nature of microorganism, as they transfer electrons to an electron acceptor through a reduced electron donor.

In order to improve the MFC performance, most researchers concentrate on cathode and microbial community. However, the anode is also a very important limiting factor for power generation as suggested by Biffinger *et al*. (2007). This is mainly due to the attachment of bacteria on the electrode, which is further enhanced by the type of electrode material used, its structure and surface area; which ultimately increases MFC performance (Qiao *et al*., 2007). Recently, Liu *et al*. (2004) found that MFCs operated by a mixed culture, can produce higher power density than those operated by a single culture. This is due to the existence of electrophiles and other groups that can be found within the natural mediators (Behera and Ghangrekar, 2009). Sedighi *et al*. (2012) and Zhang *et al*. (2011) showed that these types of microorganisms can also facilitate the transfer of electrons and protons by producing conductive nanorods.

In this research, carbon paper is utilized as the anode electrode, with different surface areas that were inoculated with mixed culture Palm Oil Mill Effluents (POME), to evaluate the effect of surface area on MFC performance.

2. MATERIALS AND METHODS

Four Plexiglas dual chamber MFCs, with 120, 160, 200 and 240 mL were used. Each of the two chambers was separated by a Nafion-117 Proton Exchange Membrane (PEM). The anode electrode was plain Carbon Paper (CP) with areas of 12, 16, 20 and 24 cm^2, assembled on four chambers of 120, 160, 200 and 240 mL, respectively. For all MFCs, CP was coated with Platinum (Pt) with a concentration of 0.35 mg cm^{-2} to be used as the cathode electrode. The anode chamber contained 3 g of glucose per liter, used as a the carbon source, 0.05 g yeast extract, used as a nitrogen source, 0.1 g KCl, 0.7 g $NaH_2PO_4.4H_2O$, 1.5 g NH_4Cl, 2.5 g $NaHCO_3$, (all from merck). 10 mL solution of mineral of wolf and 10 mL wolf's vitamin solution per liter are used as well. This composition is similar to the one used by Trinh *et al*. (2009). All electrochemical tests were conducted in a 30°C incubator in batch mode. The cathode chamber was filled with a phosphate buffer solution (which consisted of 2.76 g L^{-1} NaH_2PO_4, 4.26 Na_2HPO_4 g L^{-1}, 0.31 g L^{-1} NH_4Cl and 0.13 g L^{-1} KCl). A type of POME was used for the inoculation of the anaerobic reactor in the anode. The system was connected to a multimeter (Fluke-8846A) to measure the voltage every 15 min (Ghasemi *et al*., 2012).

The current was measured using Equation 1:

$$I = V / R \tag{1}$$

And the power was calculated using Equation 2 as follows:

$$P = I \times R^2 \tag{2}$$

where, I is the current (in Amperes), V is the voltage (in Volts), R is the resistance (in Ohms) and P is the power (in Watts). In the dual chamber MFCs, the electrons generally move from anode to cathode via an external circuit and H^+ passes from the PEM to reach to cathode as explained by Mohan *et al*. (2008).

The Coulombic Efficiency (CE) was calculated as the current over the time until the maximum theoretical current was achieved. The evaluated CE over time was calculated using Equation 3:

$$CE = \left(M \int_0^t I dt \right) / FbV_{an} \Delta COD \tag{3}$$

where, M is the molecular weight of oxygen (32 g mol^{-1}), F is Faraday's constant, b = 4 indicates the number of electrons exchanged per mole of oxygen, V_{an} is the volume of the liquid in the anode compartment and COD is the change in the Chemical Oxygen Demand (COD) over time, 't'.

Micrographs were taken of the bacteria using Scanning Electronic Microscopy (SEM, model supra 55vp-Zeiss, Germany). The details of the apparatus are given by Rahimnejad *et al*. (2011).

3. RESULTS

3.1. Bacteria Characterization and Metabolism

Figure 1 demonstrates the SEM images of the microbial communities which have been attached to the anode after two months of operation. It could be observed from the micrographs that the carbon papers were covered totally by a mixed culture of bacteria and yeasts. After characterizing of the microorganism it was undrestood that, most of the microbial structures on the anode surfaces were mainly rod-shaped.

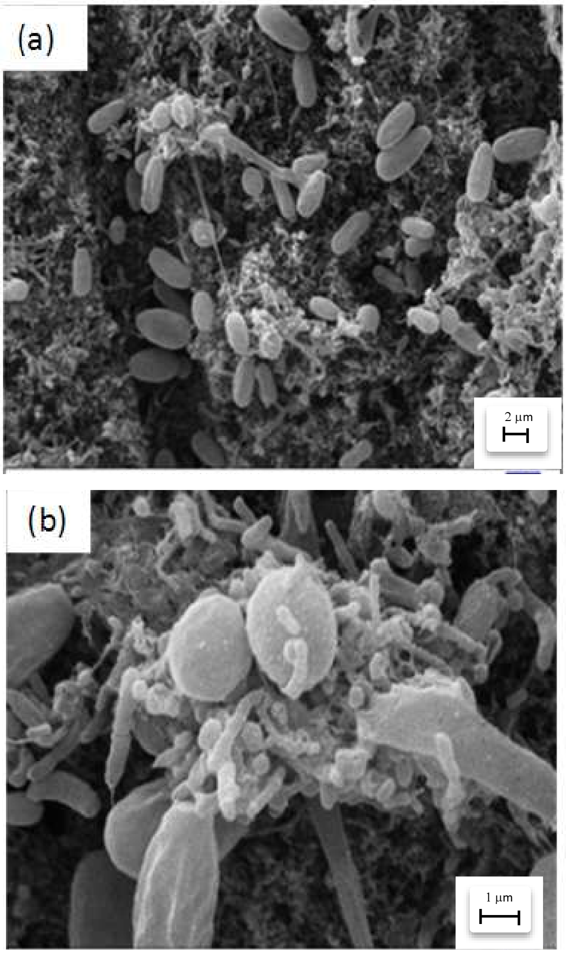

Fig. 1. Different microbial communities on the anode surface, (a) yeast (b) bacteria short rod and yeast

At 1.8-2.2 µm long and 0.25-0.4 µm wide, bacteria cells combined with cocci bacteria and some of the yeast, in sizes ranging from 3-4.5 µm.

Zhang *et al*. (2006) reported in a previous study that diversity in the microbial communities, associated with the anodes in the MFC, was observed with different shapes. The role of attached bacteria is that, they act as a biocatalyst for the conversion of organic substrates to electrons and protons.

4. DISCUSSION

4.1. Anode Performance by Different Surface Areas

Figure 2 shows the power density curve of different MFCs with different anode surface areas. The data was obtained after 2 months of working under 1000 Ω loads. The maximum power generated by the 12 cm^2 electrode was 64.681 at 328.3 mA/m^2. The power density was observed to be elevated when the electrode surface area was increased from 12 cm^2 to 16 cm^2 and reached 69.5 at 152.26 mA/m^2. This implies that more electrons were transferred from the anode to the cathode, when electrode surface area was increased. The power generated increased further at a CP anode surface area of 20 cm^2 and reached 76.5 at 178.5 mA/m^2. When the surface area was 24 cm^2, the power started to decrease to 61.25 at 221.36 mA/m^2. This decline in power density could be attributed to the mass transport limitations of organic substrates to reach the electrode surface for microorganism feeding as suggested by Lorenzo *et al*. (2010).

Figure 3 shows the polarization curve of the different MFC systems. It is used to measure the internal resistance of the system. The internal resistance of the MFCs was calculated by using the slope of the I-V curve (polarization curve). A lower internal resistance is clearly favoured by the system. The MFC working with an electrode surface area of 20 cm^2, showed the lowest internal resistance of 385 Ω among all the MFC systems. This was followed by the MFCs operating with 24, 12 and 16 cm^2 electrode surface areas, with 496, 513 and 642 Ω internal resistances, respectively. The internal resistance results calculated from the polarization curve showed that there was no special relation between electrode surface area and internal resistance of the MFC system. Therefore, internal resistance depends on other factors such as type of electrode, PEM, media composition. However, by increasing the electrode surface area, the number of microorganisms that can attach themselves to the electrode also increases. However, it should be mentioned that in agreement with the work of Logan (2009) several types of microorganisms are not suitable for electricity generation, as they consume media without producing electricity.

4.2. Coulombic Efficiency and COD Removal

Coulombic efficiency and COD removal of the different systems is shown in **Fig. 4**. It reveals that all MFC systems had high COD removal almost more than 80%. This confirms the role of MFCs in wastewater treatment by efficiently removing COD with a low capital cost. It is also observed in **Fig. 4** that the highest CE (14.7%) belonged to the electrode with 20 cm^2 surface area.

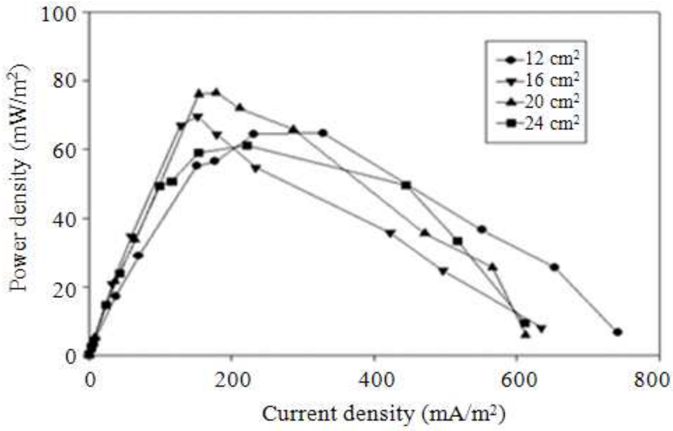

Fig. 2. Power density graph of the different MFCs

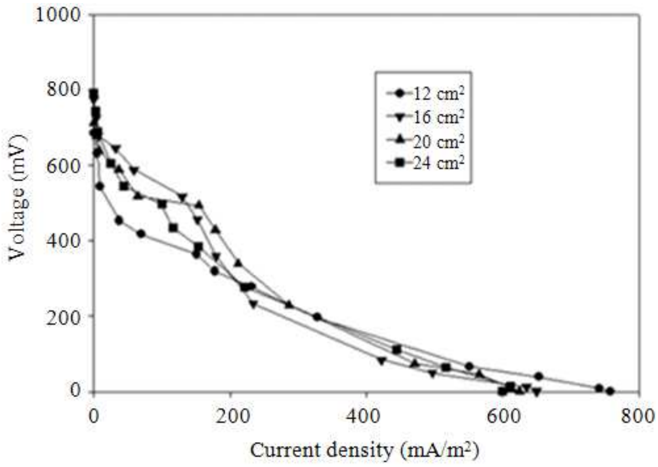

Fig. 3. Polarization curve of the different MFCs

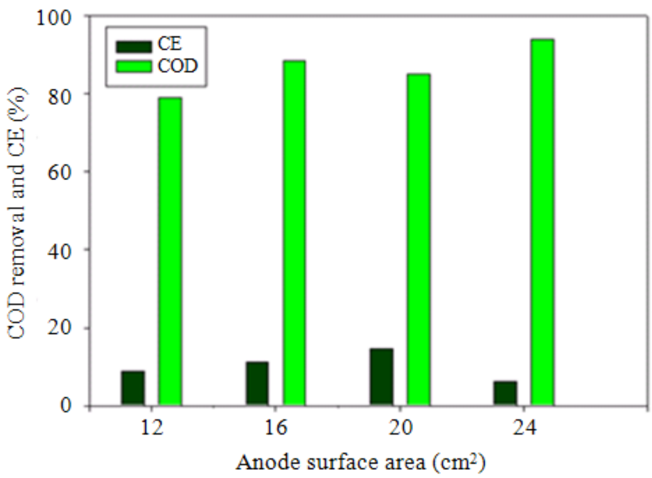

Fig. 4. COD removal and coulombic efficiency of the different MFCs

The next highest CE (11.3%) belongs to the electrode with a 16 cm^2 surface area, compared to the electrodes with 12 and 24 cm^2, which had 8.8 and 6.3% CE, respectively. This shows that the system with the highest CE percentage generated more power density.

5. CONCLUSION

Carbon paper with different surface areas was tested in an MFC. The SEM micrographs showed that several types of bacteria predominantly attached to the CP for the generation of electricity. Also, it can be concluded that after the optimal surface area (which in our study was 20 cm^2), the power density generated by MFCs declined. This indicates that the chances for attachment of bacteria and generation of electricity in larger electrode surface areas might be limited by mass transport. These findings are the basis of the next objective of this research, which is to find the optimum anode electrode area for better MFC power generation.

6. ACKNOWLEDGEMENT

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