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Effect of Electrode Surface Enhancement on the Performance of Microbial Fuel Cell Under Flow Conditions

Widyan N. Kudier [a], Shahad Z. Atta [a], Hasan Sh. Majdi [b] and Basim O. Hasan [a]*

[a] *Department of Chemical Engineering, Al-Nahrain University, Iraq."*
[b] *Department of Chemical Engineering and Petroleum Industries, Al-Mustaqbal University College, Iraq."*

Abstract

The current research investigated and analyzed the influence of electrode surface enhancement on microbial fuel cell (MFC) efficiency under different flow circumstances. In this study, two double chamber cathode and anode, identically designed and built as a completely mixed system, were run for 60 minutes using yeast, salt, water, and sugar as anode substrate. The produced electrical current in MFC was determined for smooth and enhanced surface (punched plate) of a copper electrode in double chambers MFC for a range of stirring speeds 0, 250 rpm, and 500 rpm. The effect of air pumping and dispersion in each MFC chamber on the produced current was investigated under different stirring rates. A considerable electrical current was created due to the micro-organism bioactivity on the electrode surface, which caused a difference in the electrochemical potential between the two chambers. A remarkable increase in the produced current was noticed when the flow velocity was increased in the cathode chamber. However, the flow in the micro-organism chamber reduced the amount of the produced current. Enhancing the electrode surface by increasing the contact area with the biomass causes an increased mass transfer or charge transfer between the solution and the electrode surface. As a result of surface enhancement, an increase in the current output levels depends on the flow velocity. The conjoint effect of flow velocity and aeration, especially for the enhanced electrode surface, causes an appreciable increase of the produced current in MFC, reaching up to 3 times the smooth surface. The presence of air bubbles in the cathode chamber caused a noticeable increase in the produced current density. The presence of substrate glucose showed different influences on the produced current depending on the electrode surface.

"Keywords: Current; microbial; mass transfer, aeration, fuel cell; potential; surface enhancement; micro-organism; electron transport."

1. Introduction

A large amount of energy is available in renewable sources such as solar, biomass, high-speed winds and water. It is of practical interest to utilize these sources to meet the worldwide energy demand[1-3]. With the growing need for clean energy, many feedstocks might be researched for usage for this purpose. Currently, biomass conversion into sustainable energy sources such as bioelectricity and other biofuels is critical[4]. The electrochemical behavior of active bacteria causes oxidation of the substrate in the anodic compartment, resulting in the release of electrons and protons in microbial fuel cells[5]. Both protons and electrons are combined with the electron acceptor, usually oxygen[6]. Copper is suitable for forming an active biofilm, as it is an antimicrobial metal on which the bacteria do not grow. These bacteria colonize the copper surface, forming biofilm[7].

As the microbial fuel cell "MFC" is an electrochemical system, the electrical conductivity of its electrode material plays a vital role by affecting the generated current and the produced power. The effect of electrode electrical conductivity is very influential in an up-scaled system of electrochemical performance.

*Corresponding author e-mail: basimohasan13@gmail.com; basimhasan2017@eng.nahrainuniv.edu.iq"
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Therefore, selecting suitable electrode materials for microbial fuel cells working under different operating conditions[8]. The most important physical properties of electrode surface from energy production standpoints are the surface roughness, electrical conductivity, thermal conductivity, density, adhesion, and porosity. Surface roughness may have an essential role in mass, momentum, and heat transfer in a turbulent flow conditions[9].

The effect of the roughness value depends on the ratio of roughness height to equivalent diameter or the thickness of the viscous sub-layer[10]. The roughness size, shape, distribution, flow rate, and the orientation of the roughness elements influence whether the mass transfer rate is decreased or increased. The MFC could directly transform chemical energy into electrical energy by utilizing the biological activity of micro-organisms. Therefore, it allows treating different chemical substrates at various concentrations[11].

Over the last several decades, the MFC has received wide attention from researchers to understand microbial, electrochemical, biochemical, and material surface nature specific operating conditions[12]. MFC electrodes are often made of low-cost materials, including graphite, carbon paper, and carbon cloth in the shape of plates, rods, and granules. Certain metals, like copper, nickel, and silver, have lately been discovered to be efficient electrode materials in MFC[7, 13, 14]. The use of MFC for electricity production still requires more in-depth investigation and analysis for the effect of different operating conditions[14]. The advantages of MFC are the successful removal of organic matter with energy production[15]. Several factors determine the power generated by MFC, including electrode material, surface area, surface morphology, micro-organism nature, flow conditions, pH, and so on[16]. When it comes to decomposition, temperature is a crucial factor to consider, and it is also referred to as anaerobic digestion (29,30). The optimal temperature for mesophilic bacteria is in the range of 30 to 40 degrees Celsius, and this temperature has been determined (31). Whenever the temperature goes outside of this range, the activity of micro-organisms begins to decline progressively (32). Yeast is a successful biocatalyst for MFC applications as it can metabolize different substrates. The ability of the yeast to degrade the biomass is related to the presence of various electron shuttles, cytochromes, and mediators. The existence of a high amount of proteins in the yeast cell is essential for the electrochemical behavior of species. [17, 18].

The micro-organism degrades the glucose on the electrode surface resulting in more elections as in the following equation[19, 20]:

$$C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^- \quad (1)$$

The cathodic reaction in cathodic chamber, which is oxygen reduction reaction, is:

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^- \quad (2)$$

Several studies [43; 44; 13] have investigated the effect of flow velocity on the produced current in MFC. The flow in the cathode chamber can increase the mass transport of the reactant, such as oxygen, to the surface, which enhances the current production by increasing the reduction reaction. In addition, the flow increases the turbulence level at the electrode surface, reducing the thickness of the diffusion layer and reducing the resistance to mass transfer. However, the flow in the anode region may remove the biofilm, which may restrain the oxidation process at the anode chamber and, hence, reduce the current produced. Accordingly, the effect of hydrodynamics in MFC is complicated and still need further investigation and discussion

Enhancing the electrode surface by increasing the contact area with the biomass causes an increased mass transfer or charge transfer between the solution and the electrode surface. The increase in the surface roughness may have a similar effect. In addition, increasing flow velocity on the enhanced surface affects turbulent mass transfer between the solution and the surface, affecting the MFC energy production. Studies of bioenergy production have shown that MFC soon will be one of the most practical options. A large part of the commercialization of MFC involves increasing its efficiency and lowering its price. For this reason, knowing the parameters affecting its performance and optimizing them can prove useful (32). Based on the type of wastewater (33,34), electrode materials and surfaces (35, 36, 37, 38), and anodic potential (39, 40), MFC performance differs. Barber et al. [41] used a mathematical model to investigate the contact surface area between the bipolar plate and collector. The entire contact surface area was considerably affected by three primary operating factors: bulk surface roughness, compact force, and collector coating thickness. Furthermore, the bipolar graphite's minimal porosity resulted in the collector's highest contact surface.

Only a few research have investigated and assessed the influence of the electrode surface in the cathode or anode compartment on the overall performance of the

MFC. According to the nature of MO and electrode materials, fluid flow can have distinct impacts depending on whether it is employed in the cathode or anode compartment, in general. Increasing the flow can enhance the mass transfer of MO and dissolved oxygen toward the electrode surface, which can impact the electrochemical behavior of the cell and, as a result, the output power of the cell (13)

As a result, in order to increase electricity production, it is critical to design MFCs in which the bio electrochemical interaction between bacteria and the bulk solution (substrate) may occur on the electode surface and have a significant influence. In contrast, up to this point, past research has mostly focused on the performance of MFCs by investigating the electrode, separator, catalyst, and microbial community (42,43).

The novelty of the work is to investigate the influence of electrode surface enhancement on the bio current produced in a microbial fuel cell using copper electrodes. Besides, it is aimed to examine the effect of flow velocity and aeration on the produced current on enhanced and smooth electrode surfaces.

2. Experimental work

A microbial fuel cell was constructed utilizing a copper electrode of 50×50×0.5 mm. Two MFC chambers were used, as shown in Figure 1. The two MFC chambers contain two electrodes, anode, and cathode, each in a separate beaker of 2000 mL capacity. The cathode was filled with 1500 mL of deionized water and winery micro-organism (MO) at a concentration of 3 gm/L for each beaker. “Glucose substrate” was used with a concentration of 3 g/L as the anode. Both chambers contained 0.2N NaCl to reduce the electrical resistance of the solution. The two chambers were connected by a salt bridge containing 0.5N NaCl for facilitating protons transfer between the two chambers.

The temperature of all experiments was maintained at 30^{o}C using a water bath. The current was measured by an ammeter connected to the cell terminals. A standard calomel electrode measured the potential of each electrode.

The surface enhancement effect on the produced MFC energy was studied by performing experiments using smooth copper electrodes. A perforated plate electrode was used under different operating conditions. The anode chamber must be at a lower level of oxygen to keep the process while oxygen in the cathode chamber was increased by air pumping at a rate of 2.5 L/min. The effect of flow velocity on the produced current was evaluated utilizing a mechanical stirrer connected with a two-bladed impeller placed centrally in the cathode chamber. The copper electrodes were immersed in the biochemical solution and fixed on a plastic plate. The electrodes were cleaned by a 7% concentration dilute HCl solution for 2 min before each experiment. Then, the electrodes were rinsed with distilled water, placed in ethanol for 4 min, and finally washed with distilled water. The results of the experiments were recorded after 10 minutes when the winery and substrate were placed in the solution. This time allows bacteria to grow and create a biofilm as reported by Hamad et al. [13] for the same type of bacteria that they observed 15 minutes are enough for the bacteria to grow and adapt to their surrounding. In this current work, we observed that before 10 min, the current is very small, indicating the activity of MO is negligible. After 10 minutes, the produced current appears clearly, showing that the MO starts the oxidation process. The electrochemical cell was short-circuited to start the experiments, and the produced current and electrode potential was recorded in 2 minutes intervals for one hour.

Table 1 Materials and instrumentation used in the experimental work

1.Copper electrode of 50×50×0.5 mm size	
2.Two MFC Chambers contain two electrodes anode and cathode, each in a separate beaker of 2000 mL capacity. Both chambers contained 0.2 N NaCl to reduce the electrical resistance of the solution.	**The cathode** was filled with 1500 mL of deionized water and winery micro-organism (MO) **Yeast** at a concentration of 3 gm/L for each beaker
	"Glucose substrate" was used with a concentration of 3 g/L as **the anode.**
3.Salt bridge containing 0.5N NaCl for connecting the two chambers	
4.Water bath maintained at 30 C	
5.Standard calomel electrode	

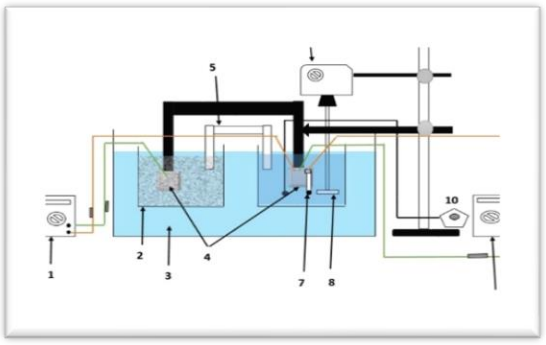

Figure 1. MFC Process Unit Schematic Diagram 1. Ammeter, 2. Beaker, 3. Water bath, 4. Electrodes, 5. Salt bridge, 6. Stirrer machine, 7. Calomel electrode, 8. Impeller, 9. Voltmeter, 10. Air pump [21]

Result and discussion

2.1. Stationary conditions

Figure 2 presents the profile of the copper electrode potential in a micro-organism chamber (anode) and a water chamber (cathode). It implies that the micro-organism compartment's potential is significantly active than the water chambers. The existence of yeast causes the potential to move to a more negative value, indicating that the MO chamber is acting like an anode. The decrease of the potential in the MO chamber is due to two main reasons. The first reason is reducing oxygen concentration, measured by Hamed et al.[13]. The second reason is the deposition of MO on the anode surface which increases the polarization resistance to be more negative. The generated current increases as the potential difference between the two chambers rises.[13, 22]

Figure 3 presents the impact of aeration on the produced current profile at T=30ºC. It can be seen that the presence of air increases the produced current density because the air raises the potential difference between the chambers, and thus the produced current is increased. Figure 4 compares the copper electrode potential trend in a micro-organism chamber with and without the presence of air pumping. The MO chamber curve in fig 2 is the same one (without air curve) in figure 4 as it represents the same process at the MO chamber,while, the other curve in Figure 4 presents the impact of aeration on the copper electrode potential profile in a micro-organism chamber. The results show that the potential is raised to become more positive in the presence of air bubbles. This increase in the potential is attributed to the rise in the dissolved O_2 concentration[23].

Figure 5 shows the influence of air bubbles in the cathode chamber (water chamber) on the copper potential profile in the MO chamber. The potential difference is higher than the potential without aeration (Figure 2).

The dissolved oxygen (DO) content is an important parameter influencing the MFC operation. Anode chamber contains low DO while cathode has high DO. The high level of DO causes a shift in the electrode potential to be more positive. In addition, high dissolved O2 facilitates the diffusion of more oxygen into the anode compartment through the salt bridge. Oxygen saturated catholytes are optimum for MFC power output[24].

Figure 6 shows the air impact on the copper electrode potentials in the water chamber. It is evident that the potential shifts to more positive in the present air. This shift is attributed to the increase in dissolved oxygen concentration.

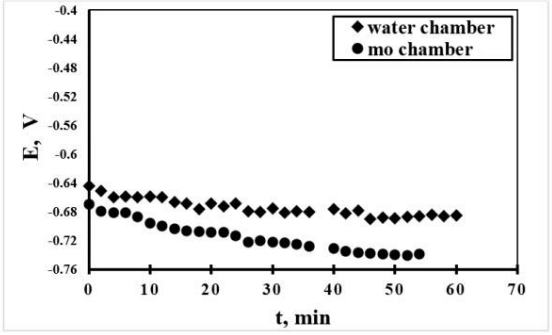

Figure 2. The copper electrode potential profile in the two chambers.

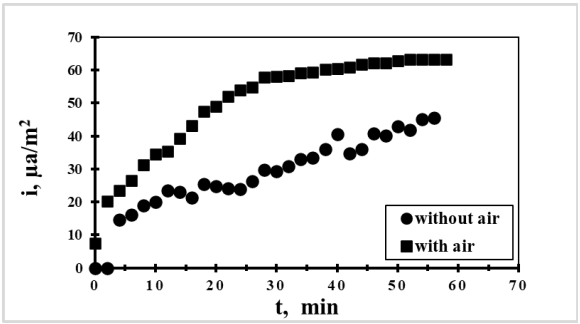

Figure 3. Impact of aeration on the produced MFC current of the cathode chamber.

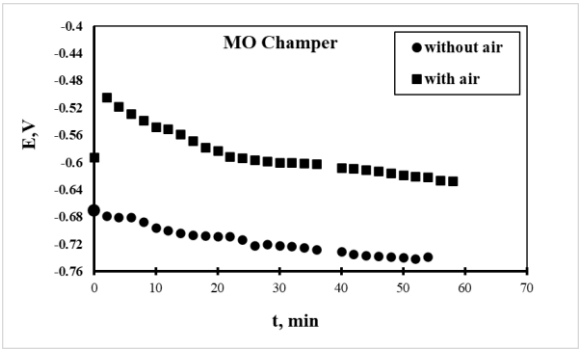

Figure 4. Impact of aeration on the potential profile in MO chamber.

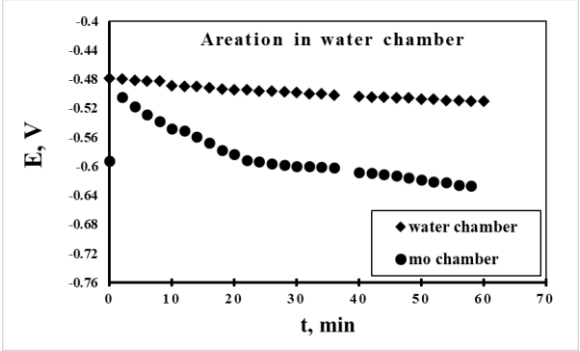

Figure 5. Impact of aeration on the MO chamber potential in the cathode chamber.

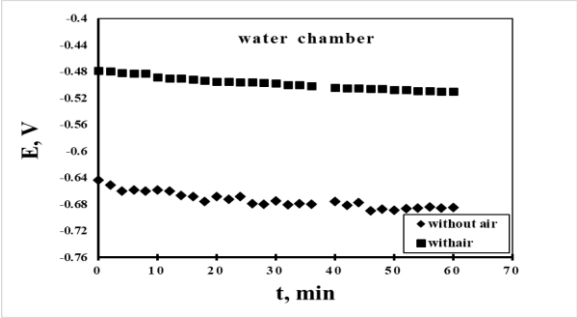

Figure 6. Effect of aeration on the cathode potential profile.

2.2. Flow conditions

Figures 7 and 8 show the impact of the flow velocity (stirring speeds) impact in the water bath on the copper electrode potentials in both anode and cathode chambers. The stirring in the water chamber at 250 rpm increases the potential difference between the two chambers considerably. It increases the potential from 46 mv (as seen in Figure 2) to 85 mv, as shown in Figure 7. A more significant potential difference exists at 500 rpm between the cathode and anode than at 250 rpm. This increase is attributed to increasing solution stirring speed in the cathode, leading to increased oxygen ion transfer to the surface electrode, increasing the electrode potential in the water chamber, and increasing cell current.

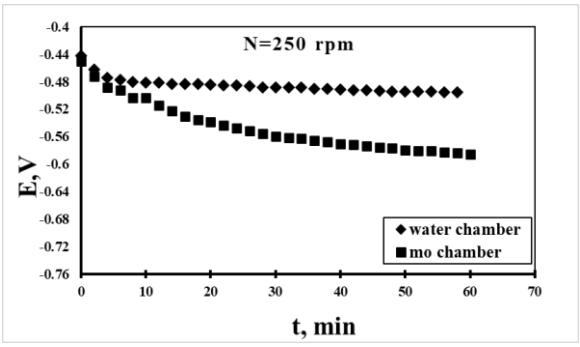

Figure 7. Potentials in the two chambers under flow conditions, N=250 rpm.

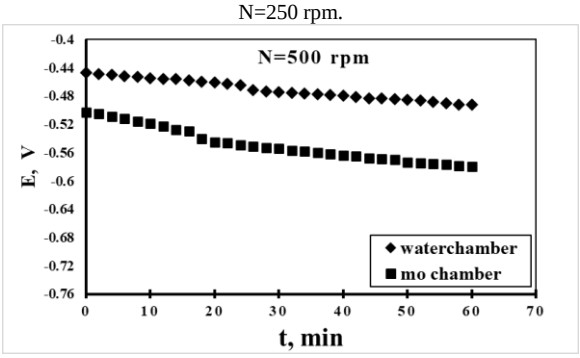

Figure 8. Potentials in the two chambers under flow conditions, N=500 rpm.

Figure 9 shows the impact of imposing different cathode chamber speeds on the produced current. In a steady-state at stirring speed 500 rpm, the current is higher than stirring speed 250 rpm by about 66%. Because Increasing solution velocity increases the current density, this increase is due to the cathode potential and oxygen transport to the electrode surface. As The yeast is anaerobic bacteria, the increased O2 transport to the surface reduces its activity at the surface. Therefore, the potential difference between the two chambers increases. In addition, the arrival of more oxygen at the cathode surface increases the electrons transfer as the oxygen is an electron acceptor.

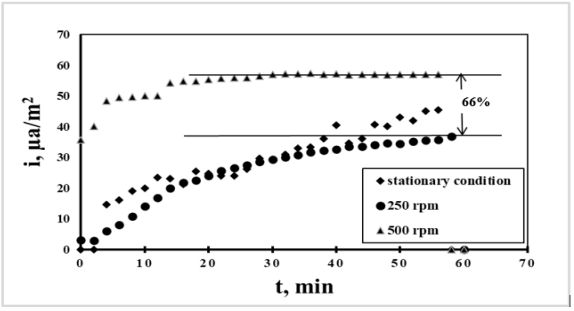

Figure 9. Effect of stirring speed on current density in MFC of the copper electrode.

Figure 10 depicts the influence of cathode compartment flow velocity in the existence of aeration on the output current density. By breaking giant bubbles into tiny bubbles, aeration and flow velocity in the water chamber promote bubble dispersion[21, 25, 27]. The dissolved oxygen level rises as a result of this dispersion. Higher oxygen delivery to the surface is caused by the strength of the flow currents ejected from the impeller, which increases the potential to acquire more positive. As a result, the potential gap widens, causing the generated current to rise. Because yeast is anaerobic bacterium, the current reduces at steady-state because increased O_2 transfer from the cathode chamber to the anode chamber induces a reduction in bacterial activity[28].

2.3. Effect of surface enhancement

Figure 11 depicts the copper electrode potential in the MO chamber when the surface of both electrodes is enhanced by surface perforating in both chambers. The potential gap between the cathode (water chamber) and the anode (MO chamber) may be shown to be quite large. The potential difference is 107 mv compared to 46 mv when there is no surface enhancement, as shown in

Figure 1. The increased potential difference can provide a higher current due to the raised driving force for the current generation.

Figure 12 shows the produced current for the case of enhanced copper electrode surfaces in both chambers. It can be seen that the improved surfaces caused an appreciable increase in the produced current. This increase is due to the increased interaction of bacteria with the electrode surface and the formation of dense microbial in the MO chamber.

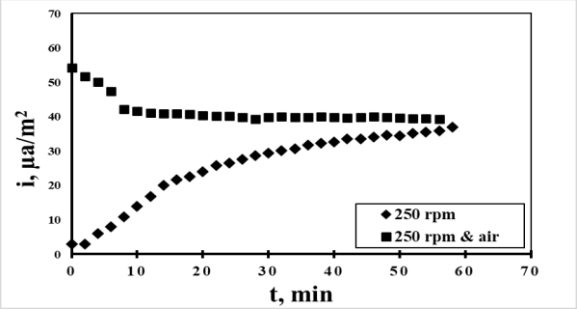

Figure 10. Impact of aeration speed on the current density profile.

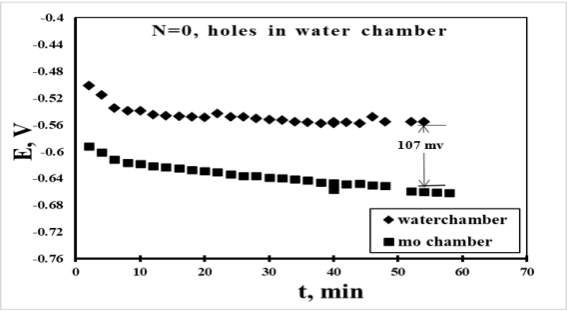

Figure 11. Potential difference for enhanced surfaces of copper electrodes.

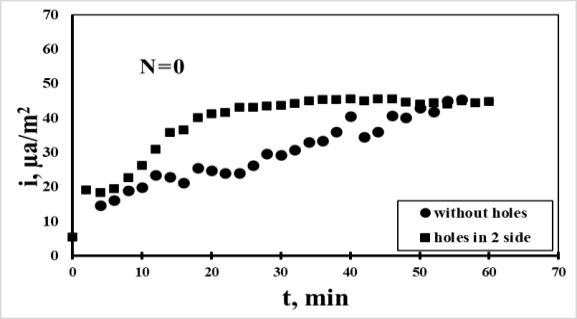

Figure 12. Produced current profile for enhanced surfaces with both electrodes is perforated.

It is thought that with increasing time, the further formation of the biofilm on the surface and on the edge of the hole increases the resistance to the current flow through the cell, which causes a reduction in the current produced by the enhanced surface to the levels of that on the flat surface. In fact, with time passage, the behavior of bio-current depends on different parameters such as biofilm thickness, MO activity, and the metabolism product. The level of these parameters will determine the behavior of the bio-current produced by MFC.

The perforations increase the interaction between the oxygen with the cathode chamber surface. The presence of sharp edges increases the oxygen reduction reaction on the cathode surface, and thus increasing the electron transfer.

Figure 13 shows the produced current profile for different stirring speeds. It can be seen that the produced current on the enhanced surface under flow conditions is much higher than that on the smooth surface. The increase in the current values is 300%. Therefore, the effect of surface enhancement on the current underflow conditions is much higher than under stationary conditions (Figure 10). This enhancement is attributed to the fact that perforation increases surface roughness. When the flow is imposed on the rough surface, the turbulence increases significantly, which causes more O2 transfer to the surface. The increased O2 arrival to the surface causes an increased oxidation and reduction reaction on both electrodes in both chambers. These results lead to an increase in the values of the produced current. At high speed, the current increases appreciably when the rate is 500 rpm because the stirring increases the cathode potential due to the increased oxygen transport to the surface. Thus, the potential difference between the two electrodes is increased. Figure 14 compares the produced current underflow velocity with aeration for enhanced electrode surfaces. It can be seen that the enhanced surface under flow conditions with aeration resulted in a significant increase of bio-current by increasing the oxygen concentration in the cathode chamber. Therefore, this produced current is much higher than the current achieved by the enhanced surface with aeration but with no changing flow conditions.

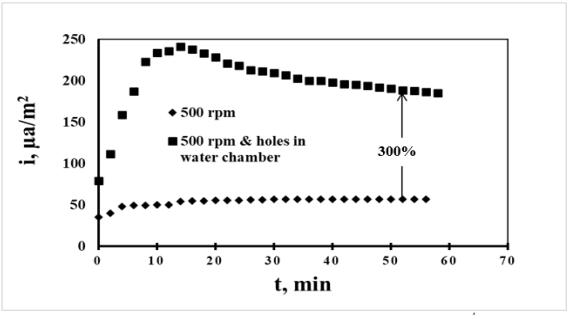

Figure 13. Produced current on the smooth and enhanced surface under flow conditions.

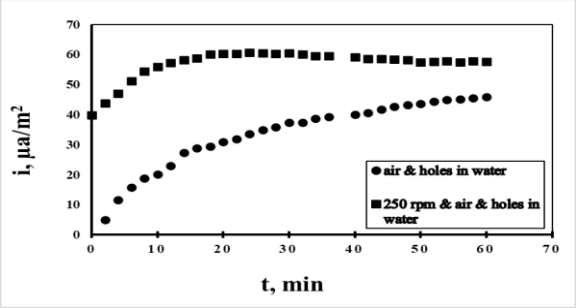

Figure 14. Current profile for the enhanced surface in the presence of air and flow velocity.

Table 2 The maximum and minimum power and current of MFC without holes and with holes

Variable (without holes)	value	Current density $\mu A_{(min)}$ (time =0)	Current density $\mu A_{(max)}$ (time=60)	Power density (min) (V) (time=0) (cathode)	Power density (V)(max) (time=60) (cathode)	Power density (min)(time=0) (anode)	Power density (max) (V) (time=0) (anode)
Flow velocity	0	0	45.48	-0.644	-0.685	-0.67	-0.739
	250 rpm	3.04	36.92	-0.442	-0.495	-0.45	-0.588
	500rpm	35.68	57.04	-0.447	-0.492	-0.503	-0.58
Air pumping	2.5 L/min	7.48	63.16	-0.479	-0.51	-0.593	-0.627
Flow velocity and Air pumping	250 rpm and 2.5 L/min	54.2	39.24				
Variable (with holes)							
Flow velocity (holes in cathode and anode side)	0	5.48	44.92				
Flow velocity (holes in cathode)	500	79.32	185.28				
Air pumping with holes in water	2.5 L/min	4.88	45.88				
flow velocity and Air pumping and with holes in cathode	2.5L/min and 250 rpm	39.8	57.2				

3. Conclusions

The energy generated by a microbial fuel cell (MFC) could be noticeably increased by enhancing the electrode surface. The current produced on the perforated surface can be three times that of the smooth surface at high flow velocity. The generated current is significantly increased when fluid flow is imposed in the cathode chamber. The produced current increases by 66% when the flow velocity increases from zero to 500 rpm. The presence of MO in the anode chamber reduces the anode's electrochemical potential, which increases the potential gap between the two chambers, leading to an improved produced current density. The potential difference is a direct function of flow hydrodynamics in either chamber. By raising the oxygen content in the cathode chamber and the potential gap, air bubble dispersion in the cathode chamber induces a rise in the produced bio-current.

The aeration of the cathode chamber increases the potential at the cathode, which in turn increases the produced current. The conjoint effect of flow velocity and aeration causes an appreciable increase of the produced current in MFC, especially for the enhanced electrode surface. The main reason for the increased produced current on enhanced surfaces is the increase in the turbulence level at the electrode surface, which increases the mass transport of oxygen from the bulk to the surface, which causes an increase in the reduction reaction.

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