Simultanous Electricity Production and Wastewater Ttreatment in a Microbial Fuel Cell Inoculeted with Anaerobic Sludge

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ABSTRACT

In order to reduce the environmental pollution associated with the conventional energy sources and to achieve the increased global energy demand, alterative and renewable sustainable energy sources need to be developed. Microbial fuel cells (MFCs) represent a bio-electrochemical innovative technology for pollution control and a simultaneous sustainable energy production from biodegradable, reduced compounds. This study mainly considers the performance of continuous up flow dual-chambers MFC fueled with actual domestic wastewater and bio-catalyzed with anaerobic aged sludge obtained from an aged septic tank. The performance of MFCs was mainly evaluated in terms of COD reductions and electrical power output. Results revealed that the COD removal efficiency up to 89% was obtained for wastewaters having an average initial COD concentration of 350 mg/L. Stabilized power outputs were clearly observed achieving a maximum value of 170 mW/ m^2.

Keywords: MFC, Anaerobic sludge, Bio-electricity generation, wastewater treatment

معالجة مياه الصرف الصحي وانتاج الطاقة الكهربائية معا في خلية الوقود الاحيائية بأستخدام الخبث البايولوجي اللاهوائي

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الخلاصة

من أجل الحد من التلوث البيئي المرتبط بمصادر الطاقة التقليدية ، ولاجل تحقيق متطلبات الزيادة في الطلب العالمي على الطاقة لذلك هنالك حاجة ماسة الى تطوير تقنيات جديدة للحصول على مصادر بديلة ومتجددة للطاقة ومنها خلايا الوقود الاحيائية (**MFC**) والتي تمثل تقنية (كهرو- احيائية) مبتكرة لغرض تنقية المياه الملوثة بالمركبات العضوية وفي نفس الوقت انتاج الطاقة المستدامة من المركبات العضوية القابلة للتحلل. هدف الدراسة الرئيسي هو تقييم اداء وكفاءة خلية الوقود الكهرو- احيائية والتي تعمل بنظام التدفق المستمر نحو الاعلى و تحتوي على غشاء تبادل البروتونات (**PEM**) والذي يفصل بين حجرتي الكاثود والانود. بالنسبة الى المادة العضوية المستخدمة كمصدر للكاربون العضوي فقد تم استخدام مياه صرف صحي حقيقية. اما بالنسبة للكتلة البايلوجية المستخدمة في تحفيز عمل البكتريا فقد تم استخدام حمأة لاهوائية تم الحصول عليها من حوض تعفين قديم .تم تقييم أداء خلية الوقود الكهرو- بايلوجية المستعملة نسبة الى كفاءة ازالة محتوى الطلب الكيماوي للاوكسجين الموجود في مياه الصرف الداخلة للمنظومة خلية الوقود البايلوجية وعلى اساس مقدار الطاقة الكهربائية المتولدة نتيجة تحلل المادة العضوية. وقد اظهرت النتائج المختبرية كفاءة ازالة محتوى الطلب الكيمياوي للاوكسجين المستهلك في مياه الصرف الصحي الحقيقية والتي بلغت 89% لمعدل تركيزCOD الابتدائي 350 ملغرام /لتر ومقدار الطاقة التي تم الحصول عليها بشكل مستقر ومستمربلغت 170 ملي واط/ $م^2$.

الكلمات الرئيسية: خلية الوقود الاحيائية، الخبث اللاهوائي، انتاج الطاقة الكهرو–احيائية، معالجة المياه الثقيلة

1. INTRODUCTION

In recent years, research activity in fuel cell technology has remarkably increased. Great expectations are directed to fuel cells because of the forthcoming depletion of Earth's fossil fuel resources (Bagotzky and Skundin, 2003). The high energy requirement of conventional sewage treatment plants are demanding for an alternative treatment technology which is cost effective and requires less energy for efficient performance. Among the new sources of clean energy, microbial fuel cells (MFCs) represent a novel technique which has gained lots of attractions in recent years. Microbial fuel cell (MFC) is a device that directly converts the metabolic power of microorganisms into electricity using electrochemical technology. It is a promising green method to treat organic effluents and produce electricity at the same time. In MFC, Microorganisms oxidize organic matter in the anode chamber producing electrons and protons. Electrons transfer via an external circuit to the cathode chamber where electrons, oxygen and protons combine to produce water (Li et al., 2009).

MFCs usually use anaerobic bacteria to oxidize the organic matter as electron donor at the anode. Then, electrons produced by bacteria via respiration are delivered to the electrode through an electron-mediated matrix or cells. When oxygen is reduced, then electrons are sent to the cathode through an external circuit for electricity generation. In two-chambers MFCs, protons are exchanged through the proton exchange membrane (PEM) to the cathode where protons combine with oxygen to form water (Kim et al., 1999; Logan 2005; Cheng et al., 2006). This inevitable requirement of an expensive PEM membrane (e.g., Nafion 117) to separate two electrodes significantly lowered its economic feasibility and considerably increased mass-transfer resistance for power production (Liu and Logan, 2004). Moreover, larger working volume in two-chamber MFCs increased spacing between electrodes thus an additional internal resistance would be resulted. The factors that influence the performance of MFCs consist of reactor operation mode (Jang et al., 2004)., strains of bacteria, types of ion exchange membrane, internal resistance, ion solution strength, electrode surface area and electrode material (Ghangrekar and Shinde, 2007; Liu et al., 2005).

MFCs have operational and functional advantages over the technologies currently used for generating energy from organic matter. First, the direct conversion of substrate energy to electricity enables high conversion efficiency. Second, MFCs operate efficiently at ambient, and even at low, temperatures distinguishing them from all current bio-energy processes. Third, an MFC does not require gas treatment because the off-gases of MFCs are enriched in carbon dioxide and normally have no useful energy content. Fourth, MFCs do not need energy input for aeration provided the cathode is passively aerated. Fifth, MFCs have potential for widespread application in locations lacking electrical infrastructure and also to expand the diversity of fuels we use to satisfy our energy requirements (Rabaey and Verstraete, 2005).

The main objective of this work was to evaluate the performance of an up flow microbial fuel cell (UMFC) fed with actual domestic wastewater and inoculated with anaerobic aged sludge. The performance of the UMFC was considered with respect to COD removal and power generation.

2. MATERIALS AND METHODS

The up flow MFC consisted of dual rectangular chambers made of transparent acrylic parallelepiped having dimensions of 52 x 9.4 x 9.4 cm. The cathode chamber (26 cm height) was located on the top of the anode chamber (26 cm height) (Figs. 1 & 2). Graphite plain electrodes were used in the MFC each had a surface area of 60 cm^2. The graphite electrodes were abraded by sand paper to enhance bacterial attachment. The two chambers were separated by a cation exchange membrane (CEM) type CMI-7000, supplied by membrane international INC., NJ. The CEM sheet of dimensions 10cm X 10cm was placed between two perforated glass sheets containing 25 pores, each of 6.77 mm diameters (Fig. 2).

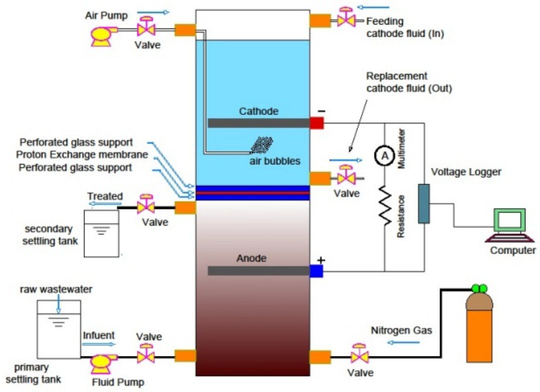

Fig.1 Schematic diagram of the MFC

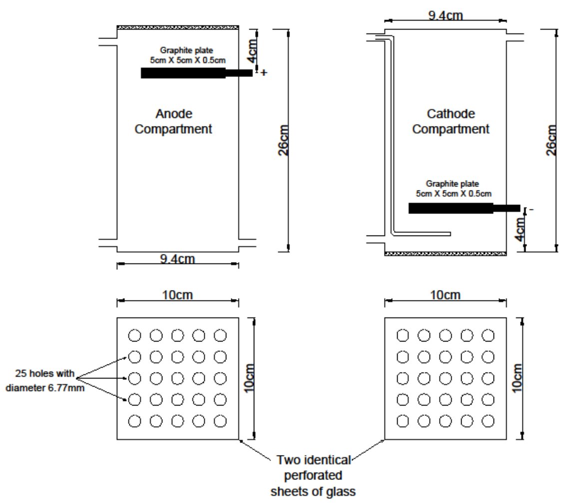

Fig. 2 Dimensions of anode and cathode chambers

2.1 Operating conditions

Before establishing the construction and set up of the MFCs systems, all the components of the microbial fuel cell were cleaned very well with proper detergent, significantly rinsed with tap water, and then with distilled water. The membrane was treated with sodium chloride solution for six hours, and then rinsed with deionized water to ensure good conductivity for protons. Upon constructing and assembling of the MEC, both the anodic and cathodic compartments were filled with deionized water, gently shaken, and then emptied. The anode in particular, was pre-treated and sterilized with boiled distilled water for 1 h, and then washed and re-treated for additional 30 min using fresh distilled water to insure the sterilization process. The cathode compartment was filled with the phosphate buffer solution (PBS) as the catholyte solution. This solution consisted of 20.74 g/L Na_2HPO_4, 3.11 g/L NaH_2PO_4, and 32.93 g/L $K_3Fe(CN)_6$. The bioreactors were operated at temperature 25±5ºC, and continuously fed with actual wastewater at a rate of 0.1 ml/min until obtaining stable power output. The average initial COD concentration in wastewater was 350 mg/L. The total hydraulic retention time (HRT) was 30 h. Wastewater fed to the bio-electro reactor had a pH ranging from 7.1 to 7.4. Granular aged anaerobic sludge which was collected from the bottom of a local septic tank was used to inoculate the UMFC. The freshly collected wastewater was obtained from the main sewer pipe at Al-Kut city, Iraq.

2.2 Analysis

The concentrations of chemical oxygen demand (COD) was determined according to the procedures described in the *Standard Methods* (APHA, 1998). Voltage was continuously measured by a multimeter with a data acquisition system and converted to power according to P=I*V, where: P = power, I = current, and V= voltage. The power was normalized by the surface area of the anodes. Columbic efficiency was calculated as the total coulombs measured divided by the moles of COD removed assuming 4 mole of electrons/mole of COD.

3. RESULTS AND DISCUSSION

3.1 COD removal efficiency

After the anode chamber in the UMFC was inoculated with anaerobic mixed consortia, the MFC was operated with actual wastewater as the feed to support the formation of biomass and subsequent adaptation to the new microenvironment. Constant substrate (COD) removal efficiency and voltage output were considered as indicators to assess the stable performance of the MFC. Microbial Fuel cell was continuously operated at stable conditions for 70 days. However, results related to COD reduction and current generation is presented in Figs 3 & 4, respectively for 45 days only. Approximately, after 10 days of continuous operation, a steady state condition was achieved. Maximum COD removal up to 89% was obtained for wastewater having average initial COD concentration of 350 mg/L as given in Fig.3. Results proved the feasibility of bio-electricity generation from wastewater treatment in MFC. The efficiency of COD removal in MFC was in a very good agreement with the maximum reported efficiency in the range of 62%–92% (You et al., 2006; Mohan et al., 2007; Rodrigo et al., 2007; Katuri et al., 2011; Yuan et al., 2011; Fangzhou et al., 2011).

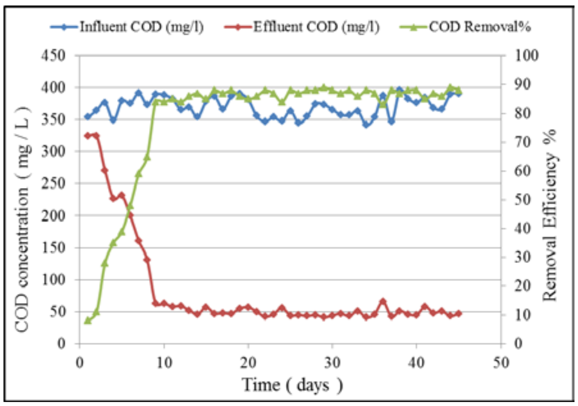

Fig. 3 COD removal efficiency

3.2 Current generation

The profiles of current generation consisted of two phases, a rapid increase during the first 10 days, followed by maximum constant value of 3.21 mA.

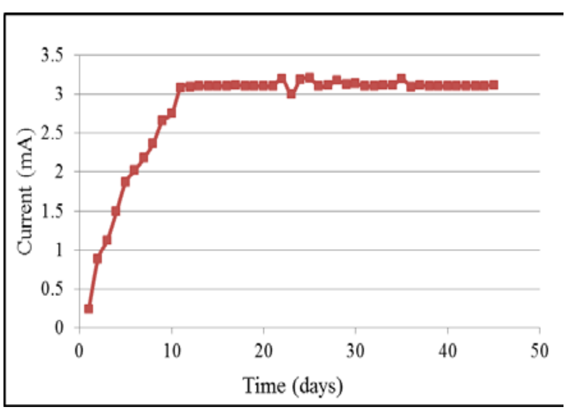

Fig. 4 Variation of the generated current with time at external resistances

The open circuit potential was 0.80 volt and the maximum closed circuit voltage drop across a continuous external resistance of 100 Ω was 0.32 volt. The variation of generated current with time for MFC is given in Fig. 4. The relationship between voltage and current at different external resistances for MFC is illustrated in Fig. 5.

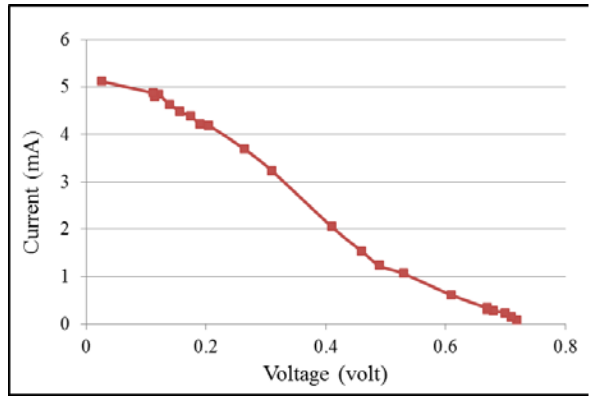

Fig. 5 Voltage-current relationship at different external resistances

3.3 Polarization curves

The relationship between the cell voltage and the power densities as a function of the cell current density is given in Fig. 6. A wide range of variable external resistances (5 -5000 Ω) was applied to demonstrate the data required for the polarization curve of the MFC. A maximum power density of 170 mW/m^2 and current density of 517 mA/ m^2 and an external resistance of 100 Ω was achieved (Fig. 6).

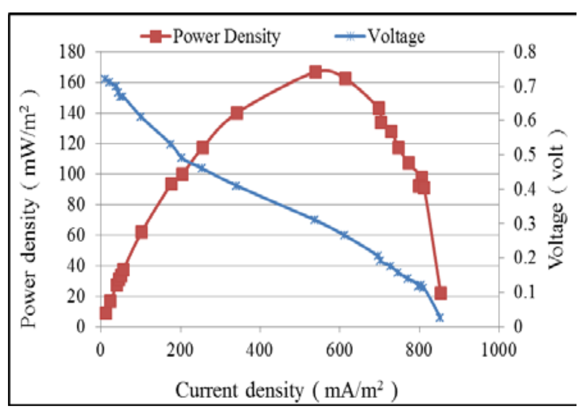

Fig. 6 Polarization curve

3.4 Coulombic efficiency

Coulombic efficiency deals with the electrons that are recovered from the substrate in the form of electric current. It expresses the rate of actual amount of electrons that is gained from the substrate in the form of electricity against the theoretical amount of electrons which are delivered by the bacteria based on the COD removal or substrate removal. The Coulombic efficiency is one of the most important indexes that were used to describe the MFC performance in terms of power generation. For continuous flow through the system, Coulombic efficiency (CE) can be calculated based on the generated current at steady-state conditions using Eq. 1 as cited by Logan et al., (2006):

$$CE = \frac{M\times I}{F\times b\times q\times \Delta S}\times 100\% \qquad \text{……………… (1)}$$

Where: F = Faraday's constant (96485 Coulombs /mol-electron), b = moles of electrons/mole of substrate (8 mole of electrons were produced as acetate oxidation in anaerobic anode chamber), ΔS= change in substrate concentration (g/L), q= flow rate of substrate (L/sec), and M = molecular weight of the substrate. The Coulombic efficiency of this MFC was 42.7%.

3.5 Effect of external resistances

To investigate the effect of external resistances on the voltage, current generation, and the corresponding COD removal, the current was recorded with different resistances across the anode and cathode to establish the relationship between the resistance and current. As presented in Figs. 7 & 8, at lower external resistance, more COD was removed resulted in a higher current generation. The results show that the bio-electrochemical reactor behaves as a typical fuel cell. At low resistance the electrons move more easily through the circuit than at high resistance, oxidizing electron carriers of the microbes in the anode. Higher fuel oxidation by the microbes is expected with high ratio of oxidized electron carriers of the culture at a low resistance.

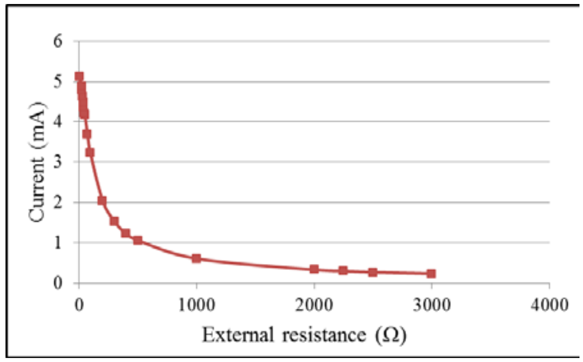

Fig. 7 Current generation with different external resistances

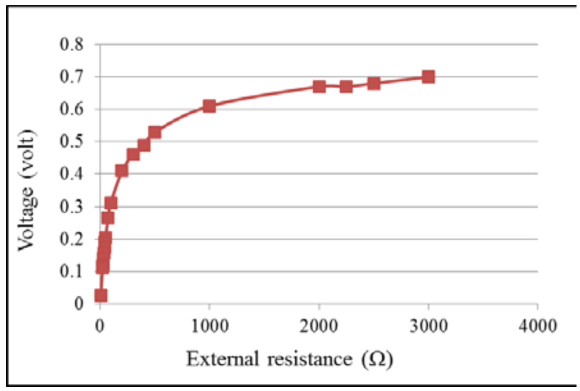

Fig. 8 The relationship between the voltage and the external resistances

3.6 BOD removal effeciency

Although the performance of microbial fuel cells were mainly evaluated in term of chemical oxygen demand (COD), measurements of biological oxygen demand (BOD) was also carried out for the MFC. As shown in Fig. 9, BOD reduction was 75%.

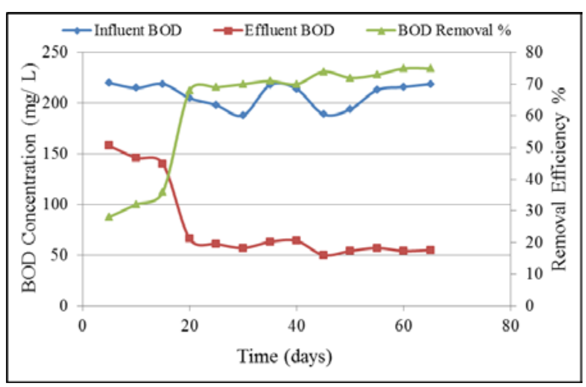

Fig. 9 BOD removal efficiency

3.7 Granulation of biomass in MFCs

Upon reaching steady state conditions in the MFC, the electrode in the anodic chamber was almost fully covered with a thick layer of bio-film and the biomass granules formation was visible in the anode chambers. After 70 days of continuous operation, the MFC was emptied and small portions of the biofilm was scratched from the electrode surface and collected for microscopic examination from anode chamber. The granulated anodic biofilms had a black color and 1-2 mm size of granules. The Scanning Electron Microscopy (SEM) images of these biofilms (Figs. 10 & 11) revealed their porous and spongy structure with some cracks on the surface. Similar observations relative to the type of biofilms were previously reported (Fang et al., 2002; Ghangrekar & Shinde, 2007). They suggested that the porous structure of granules with multiple cracks on the surface is likely to facilitate the passage of nutrients and substrates as well as the release of hydrogen, which had a very limited solubility of 1.58 mg/l in water, thus these granules did not exhibit a layered structure due to the simplicity of the acidification process.

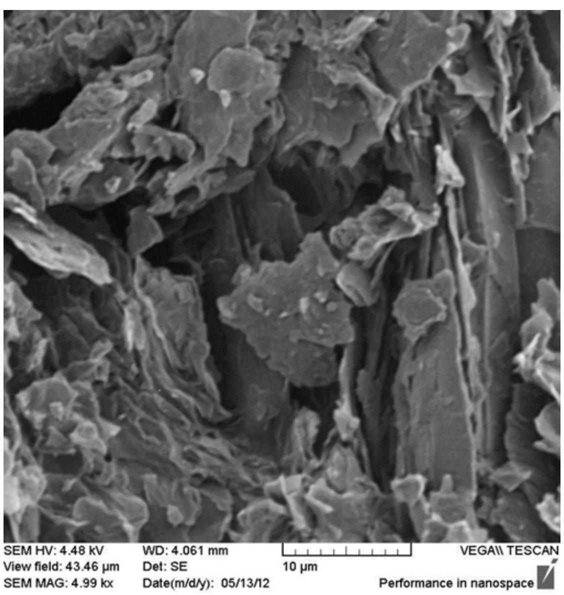

Fig. 10 SEM image for anode surface before granulation of biomass

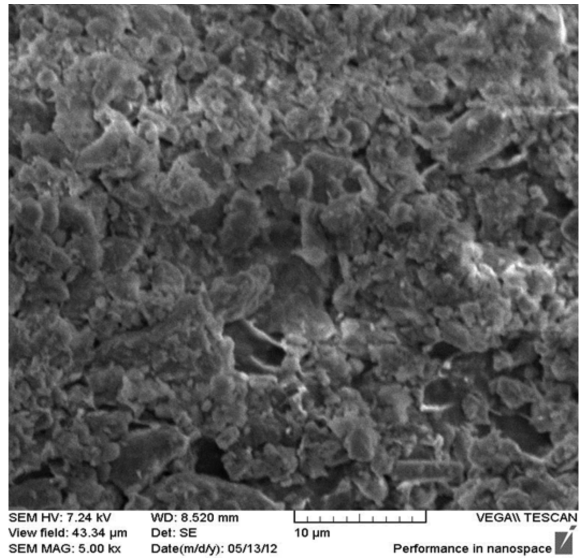

Fig. 11 SEM image for anode surface after granulation of biomass

4. CONCLUSION

This study demonstrated and evaluated the performance of an up-flow dual-chambered mediator-less microbial fuel cell (MFC) for simultaneous wastewater treatment and power generation. The performance and stabilization tendency with respect to power generation in MFC was found to be dependent on the applied substrate loading rate. Substrate degradation was observed in the anode chamber of the microbial fuel cell enumerates the functioning of an alternative anaerobic wastewater treatment unit in addition to renewable energy generation. The biofilms which grow under anaerobic environment and attached to the surfaces of the anode were the main contributors to the electricity generation. Maximum COD removal efficiency up to 89% was obtained for wastewaters with initial COD concentration of 350 mg/L. Stabilized power outputs were clearly observed achieving a maximum value of 170 mW/ m^2.

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