TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

Tổng quan về thiết kế dạng tổ ong trong pin nhiên liệu vi sinh

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TÓM TẮT

Các nhiên liệu hóa thạch khai thác từ vỏ Trái đất khi cháy trong động cơ đốt trong, động cơ phản lực để tạo ra năng lượng phát thải khí carbonic cùng các khí thải độc hại khác nên tác động xấu tới môi trường và bầu khí quyển cần hạn chế và thay thế bằng năng lượng tái tạo. Việt Nam đặt mục tiêu phát thải carbon ròng bằng không vào năm 2050 và đang thực hiện chuyển đổi sang các năng lượng mặt trời, gió, sinh khối, sóng biển. Pin nhiên liệu vi sinh là một hệ điện hóa tạo ra dòng electron bằng cách sử dụng các hợp chất hữu cơ làm chất khử và oxy trong không khí làm chất oxy hóa. Trong hai thập kỷ qua, pin nhiên liệu vi sinh (Microbial Fuel Cell - MFC) đã thu hút các nhà khoa học và công nghệ vì khả năng chuyển đổi trực tiếp năng lượng hóa học từ các hợp chất hữu cơ khác nhau thành năng lượng điện. Vì vậy, MFC là một cách hứa hẹn khai thác năng lượng từ sinh khối. Trong bài tổng quan này, một số kết quả của các phương pháp tiền xử lý sinh khối theo hướng thu hoạch năng lượng bằng MFC và các vi sinh vật được sử dụng trong MFC nhiên liệu sinh khối đã được trình bày. Ngoài ra, cách tiếp cận và thiết kế để cải thiện hiệu suất của MFC sử dụng sinh khối trong tương lai cũng được nêu. Bài tổng quan đánh giá hiệu suất và khả năng ứng dụng của các dòng chảy trong MFC dạng tổ ong, đồng thời cũng đánh giá hiệu năng hoạt động, ưu điểm và nhược điểm tương ứng, và các ứng dụng tiềm năng trong tương lai của MFC với dòng tuần hoàn.

Từ khóa: *Sinh khối, vận tốc dòng chảy, pin nhiên liệu vi sinh, thiết kế tổ ong.*

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Honeycomb designs in microbial fuel cells - A review

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ABSTRACT

Fossil fuels, the hydrocarbons within Earth's crust impact on the environment and atmosphere during burning in internal combustion engine, jet engine to produce energy have to be limited and all the countries have turned their attention to renewable energy. Vietnam will reach its net-zero carbon emission target by 2050 and call for fairness and justice in climate change issues. In order to realise this purpose, the country has to exploit more and more energy from renewable resources such as solar power, wind power and biomass. Microbial fuel cell is an electrochemical system that produces the electron current by using the organic compounds as reductant and oxygen in the air as oxidant. Over the past two decades, microbial fuel cells (MFC) have gained attention because they can directly convert chemical energy from various organic compounds into electrical energy. In MFC, biomass energy is directly harvested as electricity, the most exploitable and versatile form of energy. Therefore, MFC is a promising way to get the energy from biomass, adding a new dimension to the biomass energy industry. In this review, some results of the biomass pretreatment methods towards power harvesting by MFC and the microorganisms used in the biomass fuel MFC were summarized. In addition, strategies to improve the performance of MFC using biomass and future scenarios were highlighted. This review aims to evaluate the performance and applicability of flows in honeycomb MFC. It also assesses the respective performances, advantages and disadvantages, and potential future applications of MFCs with recirculation flow.

Keywords: *Biomass, flow velocity, microbial fuel cell, honeycomb design.*

1. INTRODUCTION

Water shortage is one of the severe global issues; according to climate change forecasts, this problem will be even more pressing in the future.[1] The increase in water demand has led to a rise in the amount of wastewater generated. At the same time, the need for renewable energy becomes immediate because of fossil fuels' rapid depletion and the growing concern about climate change. Many countries worldwide are looking for more reliable, sustainable and cleaner substitutes such as biomass to reduce the need for fossil fuels. To date, biomass can be converted into different energy products such as fuel, heat, gas, and electricity. Microbial fuel cell (MFC) is a power generation device that uses bacteria as biological catalysts in organic matter oxidation from wastewater through respiration, thereby generating electricity.[2] It has considerable potential for applications in

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wastewater treatment,[3] electrical equipment,[4] and biosensors.[5] Recently, reactor designs with a scale of several hundred liters have been developed.[6] Shifting this technology from the laboratory scale to the actual pilot scale will bring the technology closer to practical application.

Several researchers found that fluid motion impacts the energy efficiency of MFCs significantly. Increasing flow parameters such as flow rate and recirculation flow rate have been shown to enhance the power produced by the MFC.[7] Mass transport is also an essential factor in improving MFC power production due to the effects of flow regime,[8] mass-liquid transfer, biofilm formation, and the substrates.[9] Suppose the mass transfer between the substrate and the biofilm is low, some bacteria may detach from the biofilm as environmental conditions become unfavorable,[10] thereby increasing the biofilm damage, activation loss and mass transfer loss of the MFC.[11] Furthermore, most of the MFCs introduced into wastewater treatment plants have continuous flow and cyclic flow regimes,[12] which complicates the investigation of the mass transfer due to the regime caused by convection.

This paper reviews the MFC honeycomb design and analyzes the aspects of the design that affect MFC performance to focus the research direction for MFC design improvement.

2. MICROBIAL FUEL CELL

MFC is an energy-producing device with bacteria as biocatalysts, converting the energy in organic compounds into electricity. A simple MFC setup is shown in Figure 1, consisting of an anode in the anode chamber and a cathode in the cathode chamber, separated by a proton exchange membrane (PEM). MFC works on the principle that a biocatalyst oxidizes organic matter in the anode chamber, releasing protons and electrons in the process, also generating CO_2. The anode electrode captures electrons and transfers them to the cathode via the outer circuit along with the movement of protons from the anode to the cathode through the PEM. At the cathode, electrons combine with protons and oxygen to form water.[13] In MFC, the Gibbs free energy of the reaction is negative. Therefore, the MFC's electromotive force (EMF) will be positive, which indicates possible spontaneous generation from the reactions. For example, in case acetate is used as the substrate at the anode, oxygen is the electron donor at the cathode ($[CH_3COO^-] = [HCO_3^-] = 10$ mM; pH = 7; 298.15 K; $p_{O_2} = 0.2$ bar),[14] then the reaction in the battery will be:

$$\text{Anodic reaction: } CH_3COO^- + 4H_2O \rightleftharpoons 2HCO_3^- + 9H^+ + 8e^- \quad E^o = -0.289 \text{ V } \textit{vs.} \text{ SHE}$$

$$\text{Cathodic reaction: } 2O_2 + 8H^+ + 8e^- \rightleftharpoons 4H_2O \quad E^o = 0.805 \text{ V } \textit{vs.} \text{ SHE}$$

$$\text{Overall reaction: } CH_3COO^- + 2O_2 \rightleftharpoons 2HCO_3^- + H^+ \quad \Delta G = -847.6 \text{ kJ/mol; EMF} = 1.094 \text{ V}$$

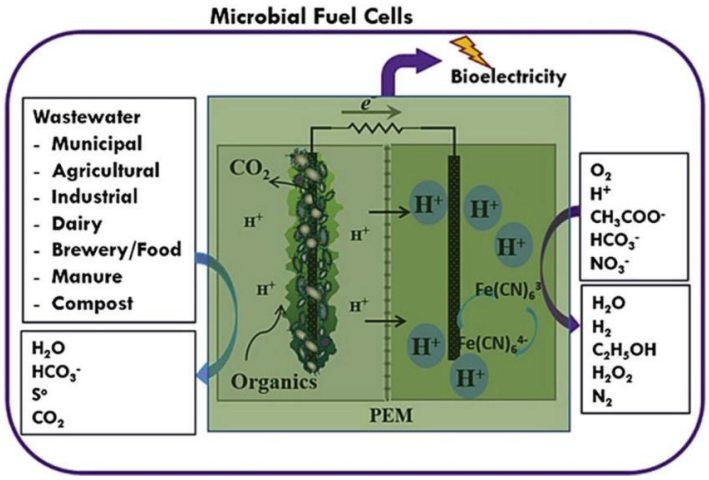

Figure 1. Structure diagram of microbial fuel cell.[15]

MFC technology has roused interest for more than 20 years not only because of the electric generation from wastes but because of its environmentally friendly wastewater treatment technology.[16] Many types of wastewater today contain many toxic wastes, which require expensive treatment before being discharged into the environment. Previous studies have demonstrated the ability of MFCs to treat wastes such as metal-derived wastewater, food, and urine and even produce drinking water after the treatment process.[17,18] MFC has coexisted with biological filter tanks in wastewater treatment to enhance pollution control and increase treatment capacity.[19] Most of the treatment methods aim to remove organic compounds that reduce chemical oxygen demand (COD), azo dyes,[20] and heavy metal waste.[21] The aeration system in wastewater treatment is reported to consume more than 54% of the electricity required in the treatment process. Since MFCs use anaerobic bacteria for the wastewater treatment process, this indicates potential energy saving in MFCs.[20] In addition, MFC-derived technologies such as MFC-based biosensors are expected to be one of its most promising applications. Having the capability to measure various parameters including bio-oxygen demand (BOD), chemical oxygen demad (COD), dissolved oxygen (DO), volatile fatty acids, toxic substances and microbial activity,[22] this device promises a reduction in time and cost in measuring the toxicity in water.

Recent advancement in the application of power generation capabilities includes the use of MFC to power a small computer (158 mW) directly and continuously without any management equipment and power source.[23]

The performance enhancement of the MFC was accomplished by using alternative electrode materials, different electrode surfaces, electroactive bacteria (EAB), substrate, and load resistance. The electrode material has a significant influence on the performance of the MFC.[24] Carbon materials are used as electrodes in MFC because they are non-corrosive, highly biocompatible, and exhibit some distinctive surface characteristics of electrode materials. Modification of the electrode material has been shown to be an effective way to improve the performance of the MFC.[25] This change in the physical and chemical properties of the electrode helps the microorganism bind and transfer electrons better. The efficiency of MFC can be increased by improving bacterial adhesion and electron transfer along with the modification of the electrode surface.[26]

The biofilm attached to the electrode is a crucial element of electrochemical bioreaction.[27] The growth and development of biofilms on the MFC electrodes, especially on the anode electrode, will help carry out the oxidation of organic matter and transfer electrons to the cathode.[28] The anode electrode of the MFC must contain a stable and homogeneous bioreactor for enhanced energy generation.[29] Biofilm cultures are often contaminated by wastewater or the entry of other competing microbial species, which can reduce performance. Next, the performance of MFC is highly dependent on the nature of the substrate. Substances can be classified into simple molecular structures such as the commonly sed glucose and acetates and more complex structures such as molasses and cellulose.[17] From a chemical characterization perspective, the nature of the substrate used by the bacteria during aerobic or anaerobic respiration will affect the electron donation rate in the MFC. This influence is based on the complexity of the different bacterial species used in the MFCs.[30]

In summary, the electrode properties and the correlation between electrode, substrate, and bacteria are the main factors affecting the performance of MFC. It can be seen that the development of MFC technology is a diverse combination of specialties such as biochemistry, electrochemistry, mechanical engineering, and materials science. Alot of work are doing in order to improve the preformance of MFC such as *(i)* the Nafion membrane[31] *(ii)* pre- treatment of biomass as bamboo,[32,33] *(iii)* hydrogen revolution directly form fermentation of biomass[34] and *(iv)* power generation with higher eficiency.[35,36]

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3. HONEYCOMB DESIGN

3.1. Structure of honeycomb MFC

The honeycomb straight-line press is a device widely used in dynamic research works and has many practical applications. They have a metal or ceramic tubular structure aligned parallel to the flow direction and have the shape of a honeycomb.[37] These structures are used to achieve different goals, such as generating shear forces with uniform geometry. They are used in wind tunnels to reduce velocities caused by the eddy motion of the air stream during entry. They are also applied in flat plate solar collectors to reduce and prevent heat loss and enhance the natural thermal convection process.[38] The application of honeycomb structure in MFCs is relatively new. To the authors' knowledge, this design was developed only by Wang et al. The honeycomb MFC design is shown in Figure 2, consisting of an anode and a cathode chamber separated from each other by a proton exchange membrane. The anode chamber has a symmetrical structure, including two booster tanks and two honeycomb structures. It is connected to a pump system to facilitate continuous flow of the liquid in the chamber.

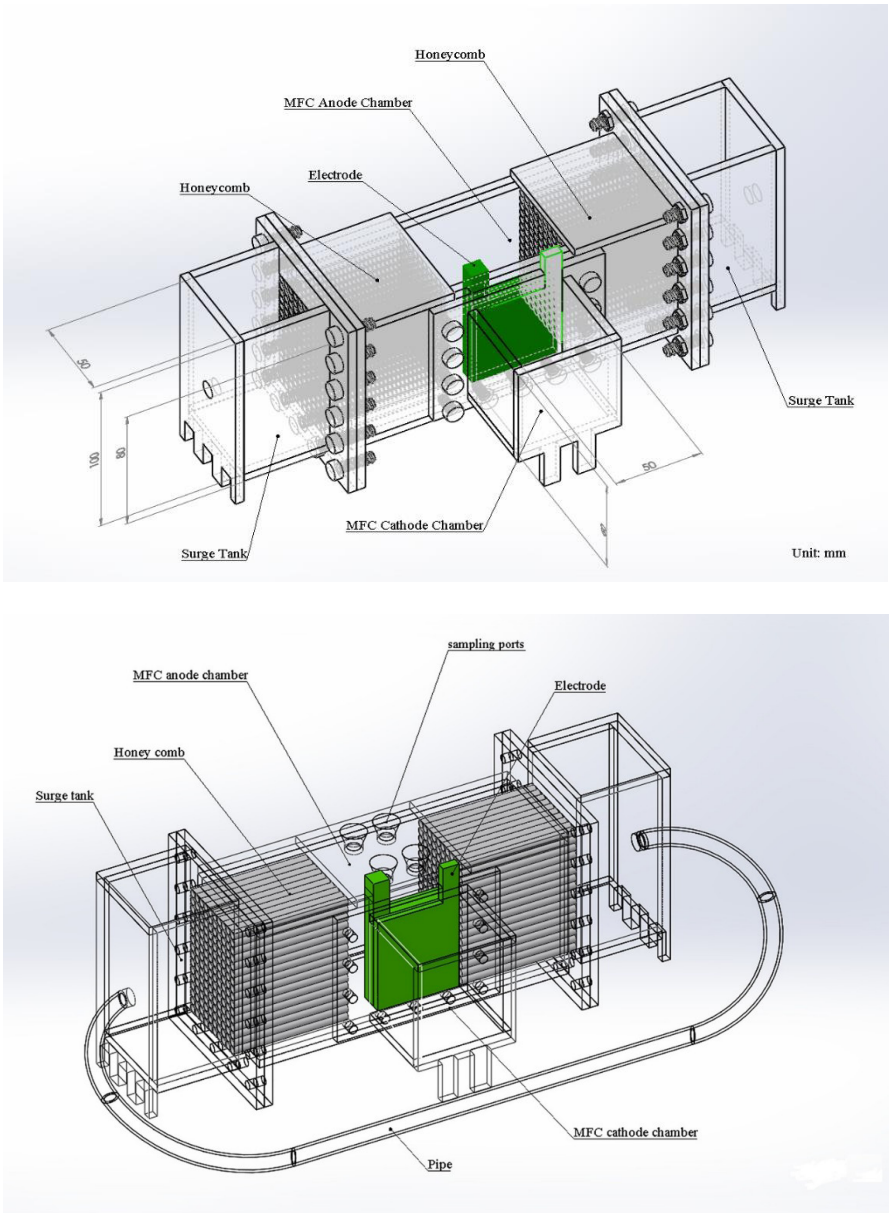

Figure 2. Perspective of two-chamber honeycomb MFC.[36]

MFC technology can be applied in wastewater treatment plants with a recirculating flow mode. The cyclical flow whill promote a mass transfer that depends not only on diffusion but also on the motion of the anode liquid.

In fluid mechanics, the Reynolds number (R_e) is a dimensionless quantity representing the relative magnitude of the influence caused by inertia and viscosity on flow resistance.[39]

$$R_e = \frac{\rho V D_T}{\mu}$$

Where: ρ is the density of the liquid (kg/m^3), V is the flow rate (m/s), D_T is the hydraulic diameter (m), and μ is the viscosity of the liquid (kg/ms). Reynolds number includes basic properties of liquids and physical quantities such as flow velocity, fluid density, and viscosity.[40] Therefore, this parameter describes the hydrodynamic effect on the power production of the MFC.

3.2. Impact of hydrodynamic boundary layer

The effect of the hydrodynamic boundary layer is a determinant of performance in a cyclic MFC reactor. The flux parameters are essential because the main component of wastewater is H_2O. Its motion has an outstanding feature in MFC performance and biological properties.[41] There are several methods used to maintain thin hydrodynamic boundary layer thickness, such as by placing the electrode near the flow inlet,[42] using thin porous electrode,[43] using flow controls to prevent the development of hydrodynamic boundary layers.[44] The working mechanism model of the hydrodynamic boundary layer effect is illustrated in Figure 3.

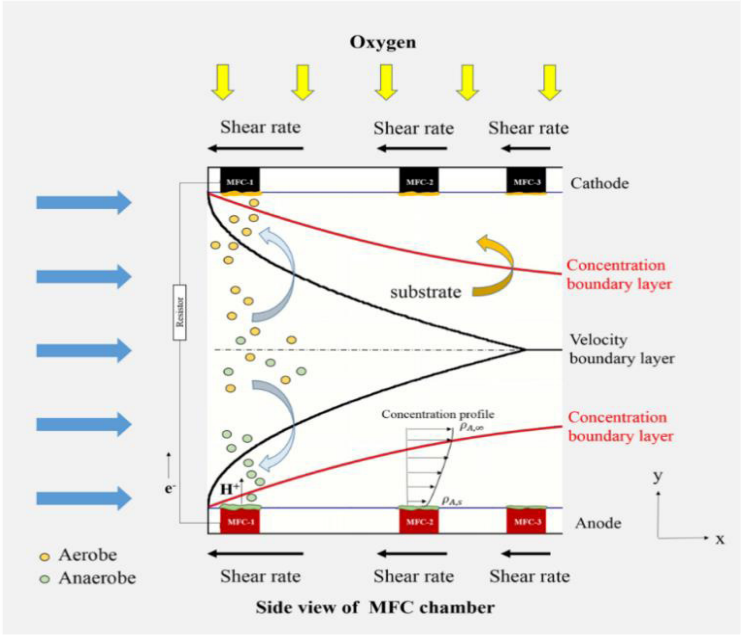

Figure 3. Diagram of boundary layers in a microbial fuel cell chamber.[45]

Figure 3 shows that the thickness of the hydrodynamic boundary layer will increase as the distance from the leading edges of the chamber wall increases. The flow velocity gradient will cause strong shear stress in the hydrodynamic boundary layer.[44] Therefore, the influence of the hydrodynamic boundary layer will affect not only the biofilm structure but also the mass transfer of the substrate.[46]

Chen *et al*.[45] tested honeycomb MFCs with various electrode distances from the chamber wall (at 1, 6, and 9 cm) to see the effect on the hydrodynamic boundary layer. It is reported that reducing the hydrodynamic boundary layer thickness on the electrode can significantly enhance biofilm formation and substrate mass transfer.

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Biofilms tend to increase their cohesion to adapt to the flow environment.[47] Li *et al.*[48] showed that the gravity effect applied to the MFC facilitated the bacterial attachment to the electrode and thickened the biofilm.

3.3. Effect of flow rate

Ieropoulos *et al.*[49] reported that the MFC performance improved when the flow rate was increased. The velocity and direction of flow can significantly affect the mass transfer of particles in the anodic solution. As mentioned, MFC current generation was directly related to the biofilm on the electrodes. The growth of thicker biofilms facilitated electron transfer to the cathode, thereby improving reactor efficiency.[50] The optimal rate in the MFC will enhance microbial activity and increase the electron transfer rate in biological media, which will reduce the activation of polarization. Meanwhile, turbulence will have the opposite effects. Wang *et al.*[51] reported that the energy density in the honeycomb MFC increased as the flow rate increased from 0 to 40 mL/min. However, as the rate increased to 240 mL/min, the power density decreased. This decrease was explained as a result of biofilm leaching at the anode. In addition, increasing the flow rate can cause oxygen permeation through the PEM from the cathode to the anode chamber. This will increase the presence of oxygen in the anode chamber which will inhibit EAB growth.

Ketep *et al.*[53] reported that the favorable environment for the growth and development of EAB was pH neutral. Under alkaline or acidic conditions, the activity of EAB in the MFC will be disrupted. It was found that the anode pH value between 7.0 and 7.55 is suitable for the operation of EAB.[54] The slow transfer of protons to the cathode compared with proton generation due to EAB activity can lead to decreased EAB activity due to their unfavorable acidic environment.[55] Maintaining the flow rate resulted in the MFC‘s ability for stability in pH.[51] Conventional methods use buffer solutions to slow acidification and maintain pH close to neutral.[56] Although using buffer solutions in an MFC system has many advantages, there is still a long way to go to scale the application because it is quite expensive. Another approach is to enhance proton transfer to stabilize pH at the anode. Cyclic mode honeycomb MFC is a promising strategy for improving proton transfer capacity, thereby improving power generation efficiency and solving the problem of using buffer solutions to stabilize the pH at low temperatures at the anode chamber.

Therefore, it can be asserted that the average velocity can be beneficial to the reactor performance due to the homogeneity of the ions in the reactor. This can lead to a large mass transfer of ions and particles to microorganisms on the biofilm and eventually to the growth and attachment of thick biofilms on the anode.

3.4. Effect of channel diameter and pipe diameter

Channel and pipe diameters are important factors in hydrodynamics. Kaji and Azzopardi[57] reported that as the pipe diameter increased, the velocity gradient decreased. The flow geometry also affects the flow velocity of the liquid in the anode. This is also demonstrated in some publications,[58,59] who affirmed that the flow velocity increases as the pipe diameter decreases. Small diameter pipes have greater resistance near the inlet. They have a circular waveform near the outlet, which is the leading cause of their chaotic pattern.

Sangeetha *et al.*[41] reported that the honeycomb channel diameter affects the removal of organic matter in the anode chamber of the honeycomb MFC. They also demonstrated that the honeycomb channel diameter affects the anode bio-thickness. Honeycomb structures with optimized channel diameters can support efficient energy and mass transfer inside the reactor.

3.5. Effect of distance between two electrodes

With respect to the influence of the anode electrode position in honeycomb MFC, Wang

et al.[60] reported that the anode-to-film distance with a value of x = 0.0 cm gives the best performance in honeycomb MFC. This could be because proton movement is restricted to the cases where the anode electrode is located far from the PEM. In addition, Xu *et al.*[61] also pointed out that the conductivity is affected by the biological fouling phenomenon that occurs on the surface of PEM when the PEM is in direct contact with the liquid in the anode.

Table 1. Studies using recirculating honeycomb reactors.

Flow rate (mL/min)	Reynolds number	Electrode spacing (cm)	Flow channel diameter (cm)	OCP** (V)	Maximum power density (mW/m^2)	References
0	0	NA	1.0	0.45	2.19	[46]
4	0.37	NA	1.0	0.67	2.93	[46]
40	3.7	NA	1.0	0.77	4.5	[46]
240	44.8	NA	1.0	0.27	2.77	[46]
0	0.0	5.0	NA	≅ 0.7	1512.4	[57]
0.06	0.016	5.0	NA	≅ 0.7	1705.7	[57]
0.58	0.16	5.0	NA	≅ 0.7	1922.3	[57]
5.83	1,6	5.0	NA	≅ 0.7	2383.5	[57]
58.3	16	5.0	NA	≅ 0.7	2422.8	[57]
58.0	16	0.0	0.7	0.62	361.8	[55]
58.0	16	3.0	0.7	0.65	130.8	[55]
58.0	16	6.0	0.7	0.68	308.6	[55]
58.0	16	0.0	0,4	0.51	333.0	
58.0	16	0.0	0,7	0.69	430.0	[36]
58.0	16	0.0	1.0	0.19	137. 0	[36]

**OCP – Open Ciruit Potential

4. CONCLUSIONS

The MFC system has a bright future not only because of using the cheaper material but also of combining techniques for generating electric power and treating wastewater. An overview of the new honeycomb MFC design has been presented and elucidated. The influence of flow and related design factors are presented in Table 1. In order to systematize optimal design conditions, the optimal reactor speed was determined at 40 mL/min. The reactors achieved maximum voltage output, power, and current density with reduced internal resistance. When the flow rate is too large, biofilm washout will occur, resulting in reduced efficiency. The effect of hydrodynamic boundary layer in recirculation MFC is a vital factor influencing mass transfer and biofilm formation. Electrode placement selection and flow control are two effective and economical methods of maintaining the hydrodynamic boundary layer thickness. The honeycomb tube diameter of 0.7 cm is optimal for enhanced COD removal and power generation efficiency. The electrode distance affects the transport of protons from the anode to the cathode.

Currently, the problems of material cost and unclear surface modification mechanisms hinder the practical application of MFC. The honeycomb design has great significance in

reducing operating costs, improving efficiency, and contributing to the operation of an MFC system with recirculating flow.

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