Microbial Desalination Cell (MDC) in the Presence of Activated Carbon

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This report studies the performance of a Microbial Desalination Cell (MDC) in the presence of activated carbon in both the cathode and anode chambers. The large surface area of the activated carbon provides surface for bacterial growth, thereby leading to the formation of a stronger microbial culture through the formation of a biofilm. An MDC of 60 ml total capacity is used to achieve 60 percent desalination within 20 hours. In addition, a maximum mean voltage of 105 mV and a power density of 1.546 mW/m^2 are obtained when a 3.2-kΩ resistor was used. The results of our experiments suggest that the addition of activated carbon to the anodic and cathodic chambers improves MDC performance. This technology has the potential to be used to integrate a waste water treatment plant and a desalination facility.

Keywords: Microbial Desalination Cell, Activated Carbon, Cellulose Acetate Membrane, Waste Water Treatment.

1. INTRODUCTION

Energy sources are required for a variety of daily needs including transportation, residential, industrial and commercial purposes. Its needs extend from powering our homes to the treatment of waste water. For instance, the activated sludge process, which is the most widely used process for the treatment of domestic sewage, requires approximately 0.349 kWh/m^3 of electrical energy. Carbon based non-renewable energy sources are a major cause of air pollution.[1] Therefore, it became a necessity to develop other renewable sources of energy that are more eco-friendly, cost-effective, and efficient. In the modern world, the treatment of domestic and industrial waste water is also an issue of great concern as it could contaminate water bodies and spread diseases. This is a result of the high concentrations of organic and inorganic substances contained in waste water which may include both soluble and insoluble pollutants.[2] According to Shizas, approximately 9.3 times as much energy, as that currently used to treat waste water by aeration processes, is contained in domestic waste water itself.[3]

A promising technology would be to harvest the energy utilizing micro-organisms capable of generating power and simultaneously treating domestic waste water using microbial fuel cell (MFC) technology. Consequently, the development of MFC technology will serve as a more eco-friendly alternative to the existing carbon-based energy sources in addition to aiding in desalination processes.[4]

1.1. Microbial Fuel Cells (MFCs)

MFC is a developing technology that uses biocatalysts to convert the energy stored in organic and inorganic substrates to electrical energy. Enzymes or even whole cells can serve as the biocatalyst for the cathodic and anodic reactions. The electrons produced during the respiratory cycle travel through a sequence of respiratory enzymes in the cell, thereby producing energy in the form of ATP. In MFC's, the terminal electron acceptor is not the microorganism (anode), but the oxygen or nitrate in the cathodic chamber.[5]

This process of transferring electrons is known as the extracellular electron transfer; it plays a major role in yielding the energy within the microbes in the MFC.[6]
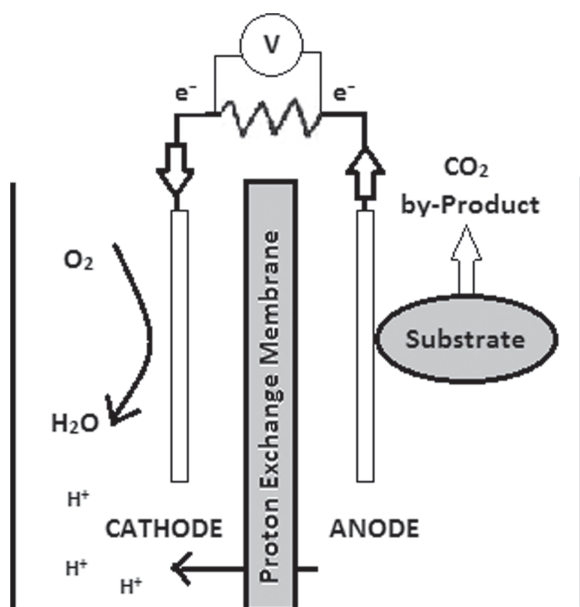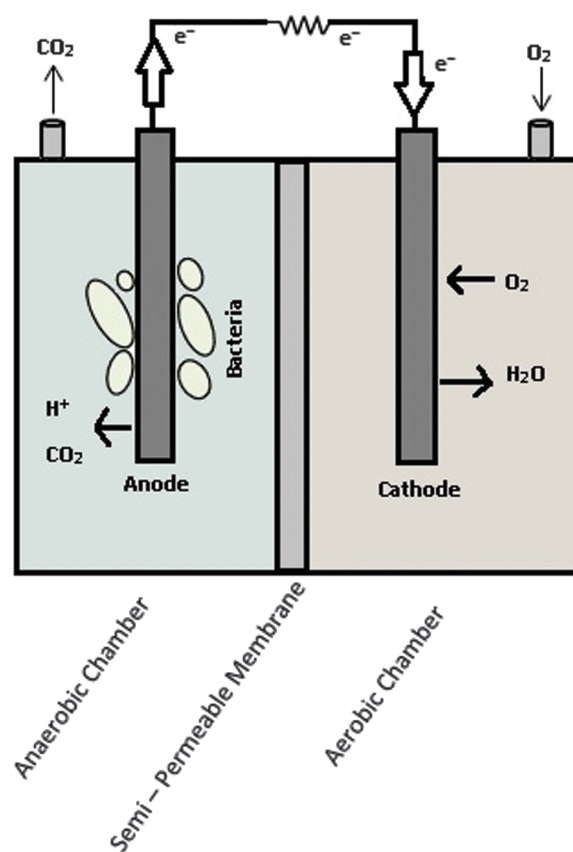

Figure 1. Schematic representation of the electron transfer mechanism in an MFC.

Figure 2. MFC working schematic.

There are a number of mechanisms through which electrons transfer to the anode. Those mechanisms can be classified as either direct or mediated, as shown in Figure 1. As the name suggests, in the direct transfer mechanism, electrons transfer from electro-active compounds to the anode through direct contact. This type of bacteria is known as exoelectrogenic bacteria or electrochemically active bacteria.[7, 8] On the other hand in the mediated transfer mechanism, the electrons transfer between the microorganism and the anode occur through soluble redox mediators.[5] The ability to pass through the cells of the microbes, nontoxicity, stability, solubility and electrochemical activity at the anode are some of the properties that should to be considered when choosing a mediator.[9]
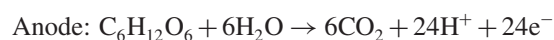
A schematic representation of a typical MFC is shown in Figure 2. It consists of an aerobic and an anaerobic chamber, the aerobic being the cathode compartment and the anaerobic being the anode compartment. A proton exchange membrane is used in separating these two chambers. In the anode chamber, the anolyte is the carbon substrate upon which the microorganisms metabolize to produce electrons, hydrogen ions and carbon dioxide. These electrons move towards the anode either directly or via mediators and then through an external resistor to the cathode. This creates a potential difference between the cathode and the anode, thereby producing bioelectricity as the electrons travel through the cell. Meanwhile, the protons (hydrogen ions) travel through the proton exchange membrane (PEM) in order to sustain electrical neutrality.[10, 11] This transfer also ensures that the excess of hydrogen ions does not disrupt the microbial activity within the anode chamber. The resulting presence of transferred electrons and protons into the cathode chamber reduces oxygen to water.

An example of the reactions at the anode and cathode are shown below.[12]

$$\text{Anode: } C_6H_{12}O_6 + 6H_2O \rightarrow 6CO_2 + 24H^+ + 24e^-$$

$$\text{Cathode: } 6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O$$

Over the years, numerous other MFC arrangements have been studied. The single-chambered, tubular, air cathode, microbial cathode, stacked, and up-flow are some of the most common arrangements.[13] An example of a single chambered arrangement is the sediment microbial fuel cell (SMFC) where the anode is deposited at the bottom of the sediment containing the organic material. Then, the cathode is placed within the water body, at the top, which in effect serves as an oxidizing agent.[5, 14] On the other hand, in the microbial-cathode arrangement, bacteria act as biocatalysts to achieve oxygen reduction without the use of catalysts such as precious metals (i.e., platinum) to improve cost-effectiveness.[15]

It is hoped that one day MFCs will be utilized as an individual method of power generation not only in our homes but also in spaceships, robots, and in the human body to support artificial medical implants by utilizing the nutrients within the human body itself.[16] There are

numerous other applications of MFCs including biosensors, desalination of sea water, production of hydrogen, and bioremediation.[17] Its most recent applications are that of energy recovery during waste-water treatment and remote power generation.

The MFC's ability to decompose organic matter with simultaneous power generation portrays its potential to be incorporated in a waste water treatment facility. Appropriate modifications in the architecture of the MFC allow for better power densities and open the door for scale-ups.[18] Of the numerous arrangements discussed earlier, the air cathode MFC has the advantages of relatively simple design and economic viability.[13]

The MFC development may be limited by certain parameters. It is nearly impossible to obtain a voltage that is equal to that predicted thermodynamically because of several losses that occur during the cells' reactions. For example, the potential energy of the cathode is utilized to overcome the activation barrier as the current is drawn from the cell. This results in activation losses which affects cell performance. Similarly, the electrons and protons transfer cause losses in voltage (i.e., ohmic losses), which also needs to be minimized. Further, mass transport losses can also occur within the cell.[12] The membrane used might limit the transfer of proton across the cell. This can disturb the electrical neutrality of the cell and may cause instablity.[19]

There are various factors that influence the performance of MFCs. The microorganism when grown as pure or mixed cultures may have significant effect on the power densities.[20] Moreover, the pH conditions in the anodic and cathodic chambers are also important factors that governs the MFC performance. In the anodic chamber, a change in pH disrupts the life cycle of the microbial community, while in the cathodic chamber, a change in pH affects the power output of the cell (i.e., A single unit increase in pH in effect decreases the potential difference of the cell by 59 mV).[21] Other factors include internal resistance, substrate concentration, electron transfer rate, H^+ transport through the membrane, temperature and ionic strength.[22]

1.2. Microbial Desalination Cells (MDCs)

A modification to the existing MFC is the MDC (Microbial Desalination Cell). MDCs are similar to MFCs but they differ in the fact that the latter consist of three chambers (i.e., the cathodic, anodic and desalination chambers). These chambers are separated using membranes. A cation exchange membrane (CEM) is used between the cathode and the desalination chamber, whereas an anion exchange membrane (AEM) is used between the anodic and desalination chambers. The anolyte and the catholyte are identical to those used in MFCs, but the desalination chamber is loaded with salt water. The AEM prevents the transfer of protons that are produced in the anodic chamber to the desalination side, and facilitates the transfer of negative ions, in the sea water, towards the anode. Similarly, the
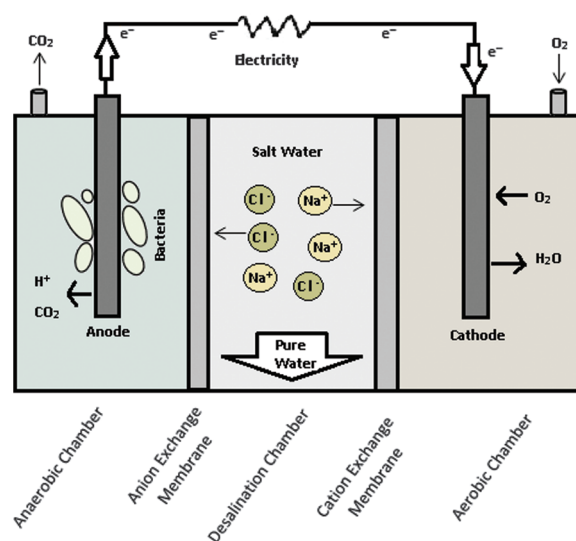
Figure 3. Schematic of three chambered microbial desalination cell.

CEM allows the transfer of positive ions from the desalination chamber towards the cathode and hence desalination is achieved.[23] The electrons produced travel through the external circuit towards the cathode, thereby producing power. The schematic representation of a typical MDC is shown in Figure 3.
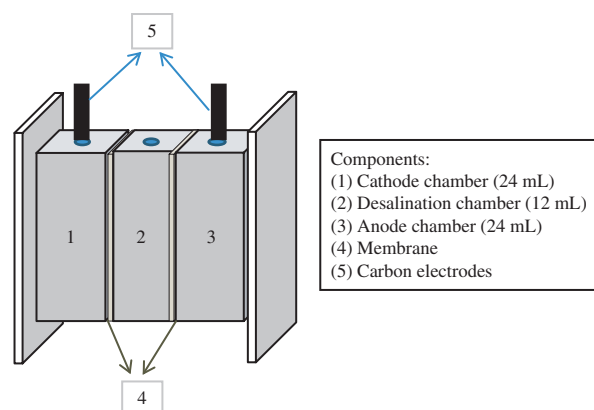
The performance of the MDC is influenced by the proton concentrations in the cathodic and anodic chambers. The continuous release of protons decreases the pH in the anodic chamber, whereas the consumption of protons increases the pH in the cathodic chamber. Moreover, a decrease in pH in the anode chamber can affect the microbial activity and increase the pH in the cathode, which may result in a significant loss in the cell potential. Therefore, it is necessary to balance the pH in both chambers. Re-circulating the cathode and anode solution with the help of an external pump would be a promising solution to maintain a constant pH in the cell.[24] Additionally, the internal resistance of the cell also increases upon variations in the salt solution concentration.[23]

MDCs have the advantage of being able to degrade organic material thereby producing power and desalinating sea water, simultaneously. It can also be used in removing heavy metals such as arsenic, nickel, copper, etc.[25] In this paper, we report on the performance of a MDC in the presence of activated carbon in both cathode and anode chambers. The large surface area of the activated carbon provides surface for bacterial growth, thereby leading to the formation of stronger microbial cultures through the formation of biofilms.

2. MATERIALS AND METHODS
2.1. MDC Setup
The constructed MDC consists of three chambers and is held together by acrylic glass plates and silicon glue.

Figure 4. Representation of a typical MDC.

Figure 5. Plot of average voltage versus time ($n = 5$). The error bars are standard deviations.

The anode and cathode chambers are present at the extreme ends with the desalination chamber in the middle. The anode, cathode, and desalination chambers are 24 mL, 24 mL, and 12 mL in volume, respectively. Thus, the total volume of the cell is 60 mL. A cellulose acetate membrane is used to separate the desalination chambers from the anodic and cathodic chambers. Both chambers are packed with activated carbon in order to increase the electrode's surface area. The activated carbon provides surface area for the bacteria to grow, thereby, supporting a stronger bacterial community/culture and the formation of biofilms. Moreover, a carbon cloth is used as the electrode and the cell is vertically oriented as shown in the Figure 4.

Salt water (at a salt concentration of 40,000 ppm) is used in the desalination chamber. The cell is connected to a data acquisition system (LABVIEW software, National Instruments, Austin, TX) and a 3.2-kΩ resistor is employed. These experiments were run five times under the same conditions for a duration of 20 hours. The total dissolved solids (TDS) of the salt water and the voltage produced in every run were measured to determine the cell performance. The data obtained were used to calculate the percentage desalination and power density of the cell.

2.2. Microorganisms and Cultivation Condition

The electrogenic microorganisms were isolated from a bottom sediment collected from "Yasna Polyana" Dam situated in the southern part of Burgas Province in Bulgaria (sampling coordinates 42° 14′54.6″N 27° 35′20.4″E).

The enrichment of the mixed culture was performed in anaerobic conditions by the inoculation of 0.5 ml sediment in 20 ml nutrient medium containing: glucose (15 g/dm^3); tryptone (10 g/dm^3); yeast extract (5 g/dm^3), NaCl (5 g/L) and a neutral pH of 7. After 96 hours of cell growth the culture was washed in isotonic saline (0.85% NaCl solution) and re-suspended in fresh nutrient medium with the same composition after dewatering. The microbial concentration was adjusted to be near 10^7 CFU/ml and then loaded into the anodic chamber of the MFC. All the cultivation steps were conducted at 18–22 °C.
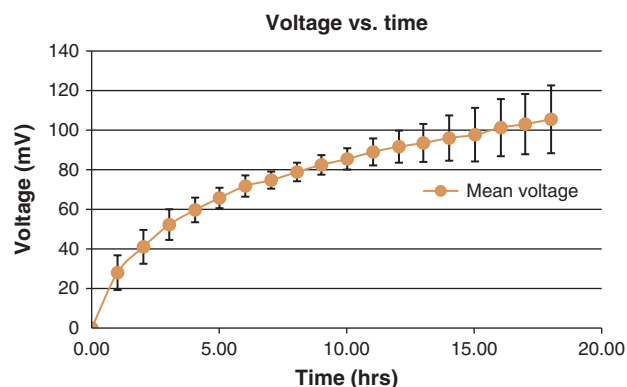
The anodic chamber of the reactor was filled with activated carbon to provide better conditions for biofilm formation and to expand the anodic surface in order to obtain better electron transfer.

2.3. Experimental Results

The results obtained ($n = 5$) are averaged and a plot of voltage versus time is shown in the Figure 5.

A maximum voltage of 105 mV is reached within 20 hours. An average power density of 1.54 mW/m^2 was achieved using our cell. Additionally, the cell is able to achieve 62% desalination in 20 hours. It can be seen from the above graph that, the voltage is steadily increasing with time due, in part, to the activated carbon which supports a stronger bacterial community/culture and increased electron transfer in the anodic chamber, through the formation of a biofilm. Also the combination of protons, electrons and oxygen that closes the circuit of the MDC is made easier by the addition of activated carbon that provides more sites for this combination to occur. The percentage desalination depends on various factors including the membrane type. In our experiments, the cellulose membrane yields 62% desalination. The experimental results are summarized in the above Table I.

Table I. Experimental results of our MDC.

Parameter	Average
TDS$_i$ of salt water	40
TDS$_f$ of salt Water	15.274
Percent desalination	61.815
TDS$_i$ of anode	5.774
TDS$_f$ of anode	14.414
TDS$_i$ of cathode	4.902
TDS$_f$ of cathode	14.216
Voltage (mV)	77.044
Power density (mW/m^2)	1.546

Note: TDS$_i$: initial total dissolved salt in (g/L), TDS$_f$: final total dissolved salt in (g/L).

3. CONCLUSION

The results of our experiments suggest that the addition of activated carbon to the anodic and cathodic chambers improves MDC performance. Although waste water provides the necessary bacterial community/culture for the MDC cell, it is a more complex process due to the larger molecular activity and more complex organic matter involved. According to our study, the power generated by the cell is efficient enough to self-sustain the cell for desalination. Therefore, this technology has the potential to be used to integrate a waste water treatment plant and a desalination facility. MDCs can also be used as a pretreatment process for reverse osmosis (RO), thereby minimizing the operating cost of these water treatment facilities.

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