

Challenges in microbial fuel cell development and operation

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Abstract A microbial fuel cell (MFC) is a device that converts chemical energy into electricity through the catalytic activities of microorganisms. Although there is great potential of MFCs as an alternative energy source, novel wastewater treatment process, and biosensor for oxygen and pollutants, extensive optimization is required to exploit the maximum microbial potential. In this article, the main limiting factors of MFC operation are identified and suggestions are made to improve performance.

Keywords Microbial fuel cell · Bioenergy · Renewable energy

Introduction

Since electrochemical activity was reported in the Fe(III)-reducing bacterium, *Shewanella putrefaciens*, and it was discovered that a mediator-less microbial fuel cell (MFC) can be operated using this bacterium (Kim et al. 1999a, b), the MFC has received a great deal of attention as a novel process for alternative energy generation and wastewater treatment. A number of excellent review papers have been written on the subject (Chang et al. 2006; Davis and Higson 2007; He and Angenent 2006; Logan 2005; Logan and Regan 2006; Logan et al. 2006; Lovley 2006a, b; Palmore 2004; Pham et al. 2006; Rabaey and Verstraete 2005). As the subject has been analyzed thoroughly in these reviews, this article will concentrate on the inherent constraints of MFCs and suggestions will be made as to how such problems may be addressed.

Power density obtainable from MFCs

The upper limit of the power level that is achievable in MFCs is not yet known because the high internal resistance limits the maximum power density (Logan and Regan 2006). Various types of MFC have been compared in terms of their maximum power density (Chang et al. 2006; Rabaey and Verstraete 2005; Jong et al. 2006). Several studies have shown that MFCs using similar microbial consortia and fuel show at least one order of magnitude difference in the maximum power density (Tables 1 and 2). This clearly shows that the performance of MFCs is determined by factors relating to reactor configuration collectively known as over-potential or internal resistance (You et al. 2006b). The power density of MFCs is several orders of magnitude lower than that of chemical fuel cells (CFCs). This is due to

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Table 1 Maximum power density in various MFCs using mixed population

Reactor type	Fuel used	Power density (mW/m ²)	Power per volume (mW/m ³)	Reference
H-type Single chamber	Landfill leachate		2,060 6,817	You et al. 2006a
H-type Bushing	Glucose	115.6 3,987		You et al. 2006b ^a
Single chamber	Glucose	766		Cheng et al. 2006a
Single chamber	Glucose	1,540	51,000	Cheng et al. 2006b
	Domestic wastewater	464	15,500	
Single chamber	Glucose	480 ^b		Cheng et al. 2006c
Two-chamber with bipolar membrane, Fe ³⁺ /Fe ²⁺ cathode	Acetate	860		ter Heijne et al. 2006 ^c
Two-chamber	Glucose	5,850		Rosenbaum et al. 2006 ^d
Two-chamber	Acetate	1,030		Jong et al. 2006 ^e
Two-chamber	Glucose, glutamate	560	102,000	Moon et al. 2006
Upflow	Sucrose		29,200	He et al. 2006

^a Permanganate as the oxidant

^b Cathode was modified with Pt catalyst and Nafion binder

^c Coulombic efficiency of 80–95% and energy recovery of 18–29%

^d Complex electrodes; tungsten carbide containing anode and graphite foil coated with pyrolyzed iron(III) phthalocyanine/polytetrafluoroethylene as the cathode

^e Thermophilic (55°C)

the various constraints inherent with the microbial device that increase the internal resistance, such as the requirement for water and inorganic nutrients, as well as differences in the anode catalysts and reactor configuration. It is necessary that MFCs should be optimized in terms of reactor configuration and electrolyte to reduce the internal resistance and enable operation to the full microbial catalytic potential (Liu et al. 2005a).

Choice of anode microbial catalyst

MFCs can be operated using pure cultures (Bond and Lovley 2003, 2005; Chaudhuri and Lovley 2003; Holmes et al. 2004a; Kim et al. 1999a, b, 2002, 2005a; Park et al. 2001; Pham et al. 2003; Prasad et al. 2006; Reguera et al. 2006; Ringeisen et al. 2006), but mixed cultures are more suitable for the use of complex fuels such as wastewater, as single

organisms generally metabolize quite a limited range of organic compounds.

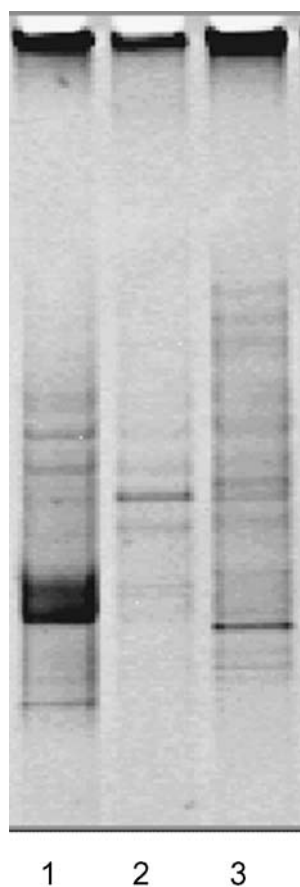
When a MFC was inoculated with activated sludge or anaerobic digester sludge, an open circuit potential of 0.6 V developed, but the current was negligible when the circuit was closed. With the repeated supply of fuel to the anode compartment, the current increased gradually to a stable value within 2–3 weeks (Kim et al. 2004, 2005b; Lee et al. 2003). Small ribosomal DNA (16S rDNA) analyses showed that the bacterial population of the anode was different from that of the sludge used as the inoculum (Choo et al. 2006; Jong et al. 2006; Lee et al. 2003; Phung et al. 2004). Figure 1 shows denaturing gradient gel electrophoresis (DGGE) results from amplification of 16S rDNA from the sludge used to inoculate the MFC and from the anode. These results show that the microorganisms involved in current generation were present in the sludge in small populations, but that they propagated while others were washed out during the initial stages of

Table 2 Maximum power density in various MFCs using pure culture

Strain	Reactor type	Fuel used	Power density (mW/m ²)	Power per volume (mW/m ³)	Reference
<i>Escherichia coli</i> , acclimated, non-mediated	Single chamber	complex medium	600		Zhang et al. 2006 ^a
<i>Shewanella oneidensis</i>	Miniature	lactate	3,000	500,000	Ringeisen et al. 2006
<i>Geobacter sulfurreducens</i>	H-type	acetate	13	355.5	Bond and Lovley 2003
<i>Rhodospirillum rubrum</i>	H-type	glucose	33.4		Chaudhuri and Lovley 2003
Clostridial isolate	Two-chamber	complex medium		5,620	Prasad et al. 2006

^a Polytetrafluoroethylene (PTFE)/graphite composite anode

Fig. 1 Comparison of bacterial communities in the microbial fuel cells enriched with acetate or glucose + glutamate by DGGE (Lee et al. 2003). Denaturing gradient used was from 30 to 60%. Lane 1: activated sludge (inoculum). Lane 2: enriched with acetate. Lane 3: enriched with glucose + glutamate



MFC operation. A similar selection process was observed in a sediment MFC (Bond et al. 2002). The nature of the enriched microbial population is dependent on the enrichment conditions (Table 3, Choo et al. 2006). It is essential

that the optimal microbial consortium be enriched for successful operation of a MFC under given conditions, which would enable efficient use of the fuel supplied.

During the enrichment process, a biofilm develops on the electrode surface (Kim et al. 2004; Logan and Regan 2006) as in MFCs that use pure cultures (Bond and Lovley 2003). Electron transfer from the biofilm-forming microbial cells to the electrode is facilitated through direct contact between them as in the reduction of insoluble Fe(III) used as an electron acceptor (Shi et al. 2006; Xiong et al. 2006) or through special pili known as ‘nanowires’ (Gorby et al. 2006; Reguera et al. 2005, 2006). Evidence has been presented, which suggests that some bacteria produce natural electron shuttles (Bond and Lovley 2005; Rabaey et al. 2004), but the importance of such electron shuttle producing organisms in MFCs has been questioned (Lovley 2006a). It is worth mentioning that the characteristics of the anode influence biofilm formation (Liu et al. 2007; Lowy et al. 2006), and that the microbial population differs between parts of the anode close to the membrane and parts away from the membrane (Jong et al. 2006; Kim et al. 2006).

Mixed electrochemically active microbial consortia for MFCs can be enriched under thermophilic (Jong et al. 2006) and psychrophilic conditions (Holmes et al. 2004c).

Rate-limiting factors in MFCs

The performance of a MFC, as well as other fuel cells, is determined by the current, power density, and rate of fuel oxidation. Various factors can influence the rate of fuel oxidation including the anodic catalytic activity, fuel diffusion,

Table 3 Comparison of bacterial communities in MFCs enriched with different fuels

Fuel (value as COD) ^a	Class (%)						Reference
	<i>α-Proteobacteria</i>	<i>β-Proteobacteria</i>	<i>γ-Proteobacteria</i>	<i>δ-Proteobacteria</i>	<i>Firmicutes</i>	Others	
Glucose/glutamate (copiotrophic, 200)	1.4	6.8	36.5	14.9	27.0	13.4	Choo et al. 2006
Glucose/glutamate (oligotrophic, 10)	64.4	21.1	3.3	0	0	11.1	Phung et al. 2004
SPW ^b (400)	27.2	40.9	0	0	4.5	27.1	Kim et al. 2004
River water (≈5)	10.8	46.2	12.9	12.9	0	17.2	Phung et al. 2004
Acetate (300)	7.0	1.7	17.3	68.8	1.0	3.8	Lee et al. 2003
Acetate ^c	0	0	0	0	24.1	75.9 ^d	Jong et al. 2006
Propionate (100)	0	19.4	22.4	10.2	0	41.8	in preparation
Marine sediment	7.5	0	2.35	70.0	11.6	14.8	Holmes et al. 2004b
Freshwater sediment ^e	0	7.0	9.7	53.5	3.0	26.8	Holmes et al. 2004b

^a COD unit was measured in mg/l

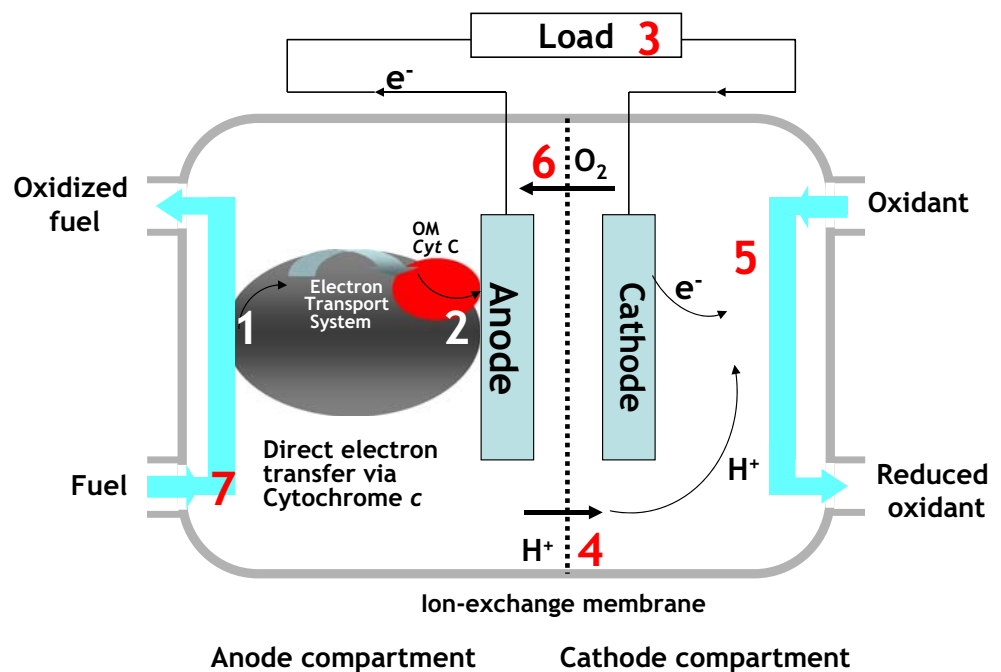
^b SPW: starch processing wastewater

^c Thermophilic (55°C)

^d Clones belonging to Phyla BIX (3.5%) and BX (72.4%)

^e The sum is 106.2% as in the source

Fig. 2 Factors limiting the performance of a microbial fuel cell (Gil et al. 2003). Anode reaction: $(\text{CH}_2\text{O})_n + n\text{H}_2\text{O} \rightarrow n\text{CO}_2 + 4ne^- + 4n\text{H}^+$; cathode reaction: $\text{O}_2 + 4e^- + 4\text{H}^+ \rightarrow 2\text{H}_2\text{O}$. 1: Fuel oxidation; 2: electron transfer to electrode; 3: resistance; 4: proton diffusion; 5: cathode reaction; 6: oxygen diffusion; 7: non-ideal fuel flow



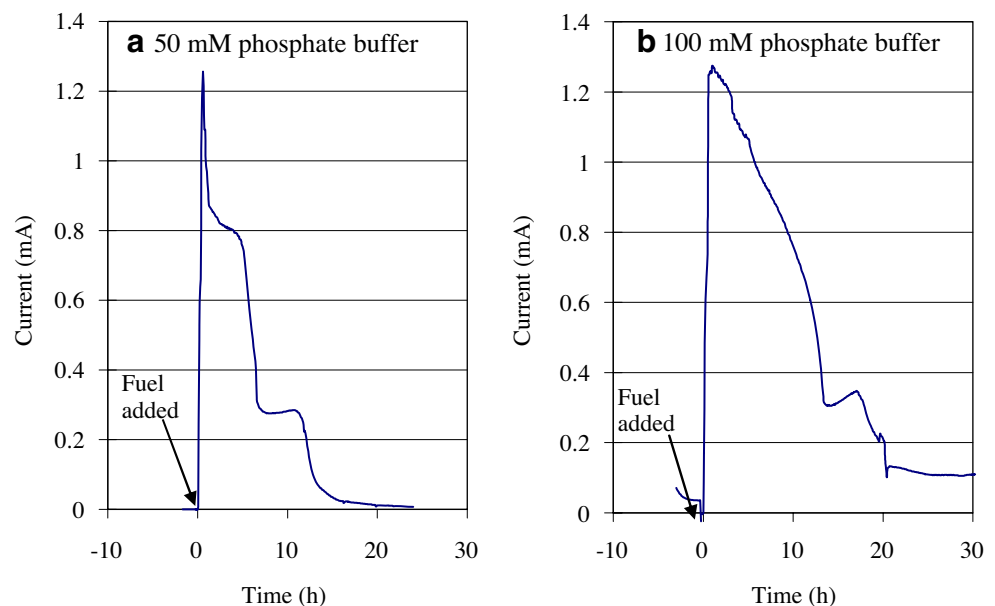
and the diffusion and consumption of electrons and protons (Fig. 2). Collectively, these manifest the over-potential or internal resistance of the fuel cell. Gil et al. (2003) described a series of limiting factors in MFCs. In a MFC operated in batch mode at a low external resistance, the current increased rapidly, but was followed by a rapid decrease, with two shoulders upon addition of fuel after overnight starvation (Fig. 3a). The first shoulder became less prominent, with a higher buffer strength in the cathode compartment (Fig. 3b), and increased aeration of the cathode compartment resulted in the second shoulder becoming less recognizable. These results showed that anodic catalytic activity cannot be

sustained due to limitations on proton mass transfer and proton and electron consumption at the cathode. Similarly, Oh and Logan (2006) observed that the size of the membrane and electrode affects MFC performance.

Proton mass transfer

As the same cation exchange membranes are used in MFCs as in CFCs, proton mass transfer would not be limited in MFCs, that have lower anode catalytic activity than CFCs, if they were operated under similar conditions. Generally,

Fig. 3 Current patterns with different concentrations of buffer as the electrolyte (Gil et al. 2003). The microbial fuel cells were fed with wastewater with a COD of 400 ppm containing **a** 50 mM or **b** 100 mM phosphate buffer containing 100 mM NaCl, respectively. The fuel cells were operated at pH 7.0, temperature 37°, and resistance 10 Ω. N₂ and air were gassed through the anode and cathode compartments, respectively, at a rate of 10 ml min⁻¹



MFCs generate current at a density 10^{-3} to 10^{-4} times lower than that of CFCs. In MFCs, the rate of proton consumption at the cathode was higher than the transfer rate through the membrane (Gil et al. 2003; Liu and Logan 2004). This discrepancy might be due to inherent differences between MFCs and CFCs. MFCs employ a variety of inorganic chemicals to support microbial metabolism in addition to the fuel, while the CFC may only have pure fuel added. The chemicals used in MFCs dissociate in the aqueous phase generating cations such as K^+ , Na^+ , NH_4^+ , Mg^{2+} , and Ca^{2+} , among others. The concentration of these cations is typically 10^5 times higher than that of protons at neutral pH (Rozendal et al. 2006; Zhao et al. 2006). These cations can interfere with proton transfer through the membrane. Another constraint for proton mass transfer in MFCs is the use of an aqueous solution as the electrolyte (Cheng et al. 2006b; Jang et al. 2004).

Rozendal et al. (2006) examined the effects of cation transport through a Nafion 117 membrane on cathode pH and MFC performance. In a two-compartment MFC, the number of positive charges of cations other than protons (K^+ , Na^+ , NH_4^+ , Mg^{2+} , Ca^{2+}) transported from the anode compartment to the cathode compartment was the same as the number of electrons transferred through the circuit. Analysis of the membrane taken from the MFC showed that K^+ and Na^+ occupied about 74% of the sulfonate residues of the membrane. The cation transport was not driven by the concentration gradient, but was an electrodialysis process. This meant that virtually no protons were transported in the MFC, and that electroneutrality was sustained mainly by transport of the cations and not by proton transport. This phenomenon causes a number of electrochemical and microbiological problems for efficient operation of a MFC. The anode compartment is acidified, raising the anode potential and producing adverse conditions for the microorganisms catalyzing the anode reaction, while the cathode compartment is alkalized, which lowers the cathode potential (Gil et al. 2003; Liu and Logan 2004). This preferential transport of cations rather than protons may be avoided by either removing the membrane (Jang et al. 2004; Liu and Logan 2004) or by using an electrolyte containing a low cation concentration.

It is known that cation transport through the membrane causes a problem in a MFC with an air-cathode. In this case, a thick film of carbonate salts developed on the cathode, which adversely affected the cathode reaction (Pham et al. 2005).

A membraneless MFC showed good performance when the two electrodes were placed as close as possible to avoid short circuiting between them (Jang et al. 2004; Liu and Logan 2004; Ghangrekar and Shinde 2007). The current increased when the cathode compartment received a salt or acid solution (Jang et al. 2004). This showed that proton

diffusion is a slow process in an aqueous phase and that proton diffusion is enhanced in an electrolyte with a higher salt concentration in a membraneless MFC. As discussed previously, salts inhibit proton transport through the membrane, but are needed for efficient diffusion of protons through the aqueous phase. In a MFC with a membrane, proton transport can be improved using a reactor with a reduced depth of proton diffusion and an anodic electrolyte of low salt concentration. The improved performance in miniaturized MFCs might be due to a reduced depth of proton diffusion (Biffinger et al. 2007; Crittenden et al. 2006; Ringeisen et al. 2006). It should be noted that a low salt concentration in the cathodic electrolyte with a limited buffering capacity leads to a shift in the cathode potential toward negative values due to alkalization of the cathode surface (Zhao et al. 2006).

When permanganate was used as an electron acceptor, a bushing MFC with increased sizes of cation exchange membrane and cathode achieved a power density as high as $3,987 \text{ mW/m}^2$, i.e. 34.5 times higher than that observed for a two-chamber MFC (Table 1, You et al. 2006b). The internal resistance of the bushing MFC was 51.2Ω with permanganate, while that of a two-chamber MFC was $1,623 \Omega$.

These results clearly demonstrate that proton mass transfer is the main constraint in a MFC, increasing the internal resistance as mentioned above.

Oxygen reduction by the cathode

Oxygen is generally used as the electron acceptor for the cathodic reaction in MFCs. Poor oxygen reduction kinetics have been well documented as one of the limiting factors for optimal MFC operation (Gil et al. 2003; Zhao et al. 2006). Graphite is a commonly used electrode material, but is a poor catalyst for oxygen reduction, with a saturation value for dissolved oxygen (DO) of more than 6.6 mg/l (Pham et al. 2004). This value is around 80% of the DO concentration in air-saturated water. To improve catalytic activity, graphite can be modified with platinum that reduces the saturation level of DO to around 2.0 mg/l with a maximum current three to four times higher than that obtained with a control graphite cathode (Pham et al. 2004). The use of platinum is limited due to cost, especially in large-scale applications such as wastewater treatment.

Hexacyanoferrate is commonly used as a cathode mediator to improve oxygen reduction kinetics. However, the reduction rate of this compound is much faster than the oxidation rate under MFC conditions. This compound is an electron acceptor rather than a cathode mediator (Pham et al. 2004; Rabaey and Verstraete 2005).

Various metals and their complexes have been investigated as replacements for expensive platinum in the cathode in

CFCs (Wang 2005). These include copper, gold, palladium/cobalt, molybdenum, tungsten, and manganese, which, due to their redox properties, mediate electron transfer from the cathode to oxygen. Similarly, Fe(III) (Park and Zeikus 2002, 2003; ter Heijne et al. 2006), cobalt complexes (Cheng et al. 2006c; Zhao et al. 2005), and manganese oxide (Mao et al. 2003; Rhoads et al. 2005) have also been studied as cathode materials in microbial fuel cells. Iron(II) phthalocyanine and cobalt tetramethoxyphenylporphyrin have been claimed to be as good oxygen reduction catalysts as platinum in some cases (Zhao et al. 2005). However, most of them were not as effective as platinum as cathode catalysts for MFCs. The most critical criterion of efficiency of cathode catalysts is their affinity for oxygen expressed as a saturation DO concentration or K_s value for the cathode reaction, as the current generation shows a Monod-type kinetic relationship with DO (Oh et al. 2004; Pham et al. 2004). The affinity for oxygen of the alternative materials has not been determined.

Oxygen is scarcely soluble in water with a solubility of around 8 mg/l when water is saturated with air at ambient temperature. When the oxygen consumption rate is higher than the solubilization rate, DO decreases to the point where the DO concentration limits the oxygen-consuming reaction. This is what generally happens in two-compartment MFCs using a water-based cathodic electrolyte. CFCs employ a membrane electrode assembly (MEA), the cathode of which is exposed to air to operate the fuel cell with a minimum moisture content for anodic and cathodic reactions. The performance of CFCs can be limited by water generated at the cathode surface, blocking oxygen diffusion.

Oxygen-reducing enzymes such as catalase and peroxidase have been used as cathode catalysts in enzymic fuel cells (Willner et al. 1998, 2006) and in MFCs (Palmore and Kim 1999). The terminal oxidases of aerobic respiratory electron transport systems have a far higher affinity for molecular oxygen than any known abiotic catalyst. Consequently, aerobic bacteria respire oxygen at maximum capacity at a DO concentration as low as 0.1 mg/l. For this reason, studies have been conducted in the use of aerobic bacteria as cathode catalysts (see He and Angenent 2006 for a review). The development of a biofilm on the cathode is important to improve the overall performance of MFCs (He and Angenent 2006).

We have observed biofilm formation on the cathode of a sediment MFC. The microbial population that developed on the cathode under closed circuit conditions was different from that which developed under open circuit conditions (Kang et al., paper in preparation). Similar observations have been made for marine and freshwater sediment MFCs (Hasvold et al. 1997; Holmes et al. 2004b) and in an artificial wastewater-fed MFC (Liu et al. 2005b). Bergel et al. (2005) observed that a power density of 0.32 W/m² was obtained from a hydrogen fuel cell with a stainless steel

cathode covered with a corroding biofilm formed in seawater, while the power density became less than 0.02 W/m² after the biofilm was removed. It is not known what was the DO concentration of the cathode compartment fed with air-saturated seawater, nor what the saturation DO concentration for the stainless steel cathode was.

The microbial population of the biofilm was not analyzed. It is probable that the MFC was operated at a DO concentration lower than the saturation DO of the stainless steel cathode. Increased MFC performance with the biofilm might be because certain chemolithotrophic bacteria within the biofilm consume electrons from the cathode to reduce oxygen as their energy conservation process. These results clearly show that a cathode with an aerobic microbial biofilm can provide improved performance. Some chemolithotrophic bacteria use water-insoluble electron donors such as pyrite and elemental sulphur and this might provide a further mechanism for removal of electrons from the cathode at the cell surface. Studies are currently being conducted to investigate this possibility.

In contrast to the above, a progressive decline in performance was observed in a membraneless MFC due to a biofilm forming on the cathode (Tartakovsky and Guitt 2006). It is likely that the aerobic biofilm of heterotrophic organisms reduced the availability of oxygen to the cathode. Heterotrophic microbial growth is also possible on the anode of a membraneless MFC through utilization of the unused fuel that passes through the anodic compartment (Jang et al. 2004).

Electron acceptors other than oxygen

In addition to hexacyanoferrate described above, permanganate has also been used as an electron acceptor (You et al. 2006b). A two-chamber MFC using permanganate as the cathodic electron acceptor (oxidant) generated a maximum power density of 115.6 mW/m², which was 4.5 and 11.3 times greater than that produced by using hexacyanoferrate (25.6 mW/m²) and oxygen (10.2 mW/m²), respectively. This can be attributed to the higher open circuit potential (OCP) provided by permanganate in the MFC. These results again show that the cathodic reaction is a serious limiting factor in a MFC.

Behavior of MFCs in a stacked arrangement

A redox potential of 0 V was observed against a natural hydrogen electrode at pH 7 when cell suspensions of electrochemically active bacterial species were tested by cyclic voltammetry (Kim et al. 1999a, 2006; Park et al. 2001; Pham et al. 2003). With the redox potential of

oxygen (+0.82 V) at standard conditions, a maximum open circuit of 0.82 V is expected, and, in fact, a maximum open circuit potential of 0.8 V has been reported in a MFC (Liu et al. 2005b). The MFC potential cannot exceed this value. MFCs can be connected in parallel to produce a higher current and in series for a higher voltage, as current and voltage are too low in individual MFCs for practical application of MFCs as an alternative energy source. Few studies have attempted to characterize the behavior of MFCs connected in parallel or in series (Aelterman et al. 2006).

The current of six MFCs connected in parallel was similar to the sum of individual MFCs, while the voltage was similar to the average of the individual MFCs. When they were connected in series, the voltage was similar to the sum and the current similar to the average. This behavior is well documented in electrochemical devices including CFCs. During early stages of MFC operation under stacked conditions, some MFCs show a reverse of polarity. Aelterman et al. (2006) reported higher power at later stages of operation and dissimilar performances among the MFCs used in their study. In addition, the bacterial population was different between samples collected at different time points. These results show that the early reversal of polarity might be because the MFC bacterial populations were not fully enriched during early stages of operation.

The MFC as a wastewater treatment process

Although MFCs have been studied as an alternative energy process, their application might be limited to specific areas because the power output is too small for reasonable utilization. Various wastewaters have been used as fuel in MFCs (Kim et al. 2004; Liu et al. 2004; Min and Logan 2004; Min et al. 2005; Oh and Logan 2005; Yokoyama et al. 2006; You et al. 2006a). The application of MFCs in a wastewater treatment process has several advantages over existing processes. In addition to energy recovery as electricity in a wastewater treatment process, MFCs generate less excess sludge in a more stable condition than the aerobic treatment process.

Wastewater treatment processes generate huge quantities of excess sludge that need to be disposed of. Sludge disposal is expensive and incurs a major cost in wastewater management. In an aerobic process, microorganisms utilize all the energy carried by the organic contaminants, while only a small part of the energy is available to microorganisms in MFCs for their growth, as a large part is converted to electricity. As electrochemically active bacteria have a redox potential of around 0 V against the saturated hydrogen electrode as stated above (Kim et al. 1999a, 2006; Park et al. 2001; Pham et al. 2003), the electrochemically active microorganisms in a MFC use free energy available

from the oxidation of the contaminants to reduce the electrode through the cell surface electron carrier with a redox potential of 0 V.

Assuming that electrons from the contaminants are transferred to pyridine nucleotides with a redox potential of -0.32 V and that oxygen is used as the terminal electron acceptor, about $1/3\{\Delta G^0 = -nF[0 - (-0.32)]\}$ of the energy carried by the contaminants is used by the microorganisms, and the remaining $2/3\{\Delta G^0 = -nF[0.82 - 0]\}$ is converted to electricity (Fig. 4). Preliminary results have shown that the yield in a MFC is about $1/5$ that of an aerobic culture (Jang et al., paper in preparation). This demonstrates that MFCs can substantially reduce sludge disposal costs in wastewater treatment.

In addition to easily assimilable organic contaminants, some xenobiotics are also metabolizable under microbial fuel cell conditions (Jang et al. 2006).

The effluent from a wastewater treatment process should meet the purity standards set by the appropriate authorities. The power output (fuel oxidation rate) has been reported to be a function of fuel concentration expressing a Monod-type relationship (Min and Logan 2004). The half-saturation constant (K_s) ranged from 79–103 mg/l on glucose (Liu and Logan 2004) and 461–719 mg/l on wastewater (Min and Logan 2004), depending on the operational conditions. These values show that MFCs should be operated under suboptimal fuel concentration conditions for the effluent to meet the required standards. It is for this reason that MFCs should be optimized not only for power generation, but also to treat wastewater efficiently in terms of effluent quality. It is worth mentioning that an oligotrophic MFC can be operated with a fuel concentration (as BOD value) as low as 5 mg/l (Moon et al. 2005a; Phung et al. 2004).

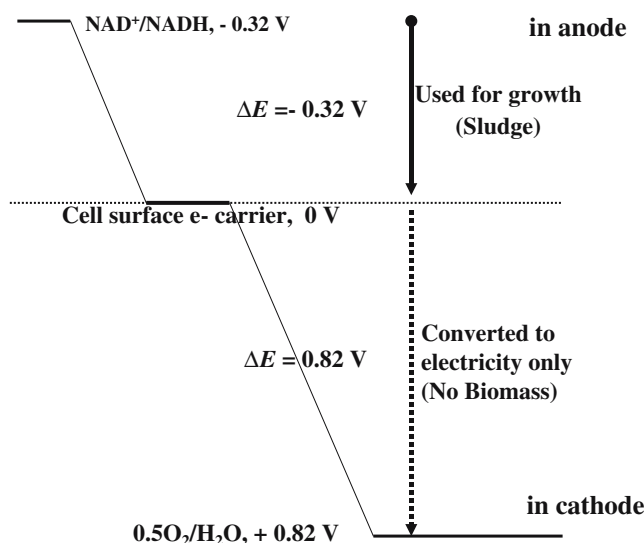


Fig. 4 Energy conversion in a MFC

Prospects and conclusions

A MFC is a novel wastewater treatment process with energy recovery from the waste. Analyses of the literature show that the performance of MFCs is limited by their internal resistance derived from proton mass transfer and poor oxygen reduction kinetics at the cathode. As proton transfer through the aqueous phase is slow, the depth of proton transfer should be minimized to reduce internal resistance through improvement of proton mass transfer from the anode to the cathode. This might be possible through the use of hollow fibre-type reactors. Inorganic compounds added to the anodic compartment as nutrients result in high cation concentrations that can inhibit proton transfer through the cation-specific membrane. Development of a proton-specific membrane may be a means of solving this problem.

Oxygen reduction by the cathode shows a Monod-type relationship with dissolved oxygen concentration. Biological redox materials including aerobic bacterial cells have a much higher affinity for oxygen than any of the known abiotic cathode materials used in fuel cells. Several papers have reported improved fuel cell performance using a cathode with aerobic bacteria, including those that develop as a corroding biofilm. It is expected that a properly enriched cathode microbial consortium could further improve oxygen reduction kinetics.

Although MFCs have not been operated to the full capability of the anodic microbial metabolism because of the internal resistance limitations, it is essential to understand the microbiology of the anodic microbial catalysts and the associated mechanisms of electron transfer to the electrode.

Fuel oxidation takes place at the surface of anode, which is uncommon in large-scale bioprocesses. The engineering aspects of MFCs, therefore, should also be considered (Moon et al. 2005b).

As the current from a MFC is proportional to the concentration of assimilable organic contaminants, this microbial device can also be used as a biochemical oxygen demand sensor (Chang et al. 2004, 2005; Kim et al. 2003a, b).

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