Microbial Desalination Fuel Cells: Assessment of technology status and potential benefit for Reclamation

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Abstract

In recent years, the number of publications regarding microbial desalination cells (MDCs) has been increasing. This technology is touted as a new method of desalination that requires no electrical energy input. MDCs combine two technologies: fuel cells and electrodialysis; therefore, MDCs are capable of producing energy and desalinating water. The water to be desalinated resides in a chamber in the middle of the cell and current produced by bacteria on the anode drives ions from the middle chamber to the anode and the cathode, thus desalinating water.

There are a number of potential benefits of MDC technology. First, MDCs have the potential to treat many different types of impaired water including wastewater, brackish water, produced water, and seawater. Second, these systems may benefit small, rural, and remote communities because of the fact that they require little to no energy input, treat wastewater, and produce fresh water. However, the technology is still relatively new has not been demonstrated at a scale large enough to be employed in the water treatment industry.

This paper documents the developments of the technology by summarizing the literature available on this topic and the potential benefits of the technology in regards to Reclamation's mission.

1. Introduction

In many areas of the Western US, fresh water supplies have been fully allocated and there is a need to develop new sources of water to meet increasing water demands. Climate change and the increasing population are placing a strain on conventional water supplies. In order to meet the growing water demand in the Western US, additional water supplies must be developed. New water supplies that can augment fresh water supplies in the Western US include brackish or impaired groundwater and oil and gas produced water. These water sources will most often require desalination in order to meet the water quality requirements of municipal and agricultural uses.

Two key obstacles limiting more widespread use of desalination technologies in rural arid regions of the southwestern United States are cost and ease of operation. Energy often represents the largest contributor to operation and maintenance costs of desalination systems. Additionally, desalination systems are viewed as complex and requiring support that is not readily available in rural areas, including access to large amounts of grid power. The industry standard technologies for desalination include membrane and thermal desalination technologies. These processes are inherently energy intensive and are prone to organic and inorganic fouling which further increases the energy consumption and requires the use of chemicals and operator time for cleaning.

Microbial desalination fuel cells can utilize wastewater containing bacteria and organic material to desalinate a brackish water source. This white paper describes the microbial desalination cell technology and the current and past research conducted in this area. Additionally, consideration is given to ways in which this technology may contribute to expanding water supplies in the Western United States and the key research challenges that need to be overcome for the technology to be used at the commercial scale.

2. Microbial desalination cell technology description

The concept of microbial desalination cells (MDC) evolved from microbial fuel cell (MFC) technology. Both MDC and MFC employ bio-electrochemical reactions where oxidation of organic compounds on the anode supplies the electrons and protons that reduce oxygen on the cathode. This reaction produces electricity as electrons flow between the two electrodes.

MDCs differ from MFC in that they employ an additional chamber, or chambers, between the anode and the cathode that contains saline water. An anion exchange membrane (AEM) is the boundary of the saline water chamber on the side of the anode and a cation exchange membrane (CEM) lies between the saline chamber and the cathode. The efficiency of the MDC process can be improved by adding additional saline water chambers to the cell.

Naturally occurring bacteria are used on the anode. These bacteria survive and grow as a result of the addition of organic matter (commonly acetate). Through a bio-electochemical reaction, the bacteria release protons into the water. Protons cannot move to the cathode because they cannot diffuse through the AEM. Therefore, in order to maintain change balance in the anode chamber, anions flow from the middle desalination chamber to the anode. At the cathode, protons are removed from water, so cations move from the middle chamber to the cathode chamber to maintain the charge balance. The following is a basic schematic of a basic three chamber MDC, Figure 2.

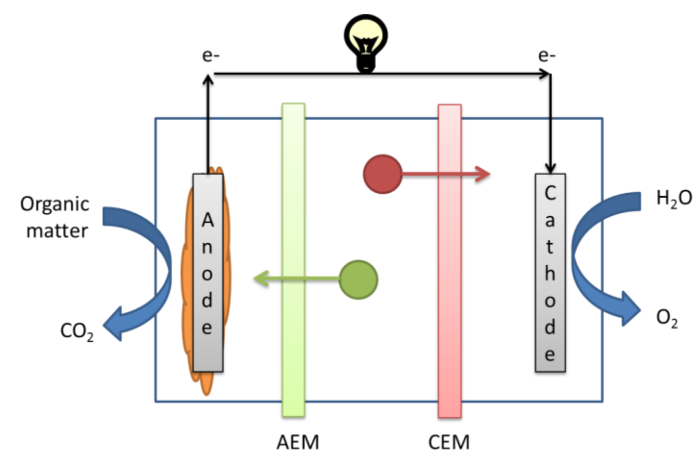

Figure 2. Schematic diagram of a basic, three chamber MDC.

The first proof-of-concept demonstration of the MDC technology utilized ferricyanide as the catholyte, however, this is not a sustainable choice of catholyte and further work has since been conducted using an air cathode (Mehanna, Saito et al. 2010).

3. Review of microbial desalination cell literature

Recently, there has been an increase in the number of publications appearing in the literature regarding microbial desalination fuel cells. Many of these studies claim that microbial desalination fuel cells may be a promising technology for the desalination industry due to the ability of the technology to treat both wastewater and saline water with minimal electrical energy input.

The first study published in the literature regarding MDCs was in 2009 by Cao et al. who conducted pioneering experiments demonstrating a three chamber, batch operated, MDC (Cao, Huang et al. 2009). Since this first publication in 2009, the number of publications per year has been increasing almost exponentially, illustrating the interest from the water treatment community in this emerging technology. The following graph depicts the recent interest in this technology by reporting the number of publications per year.

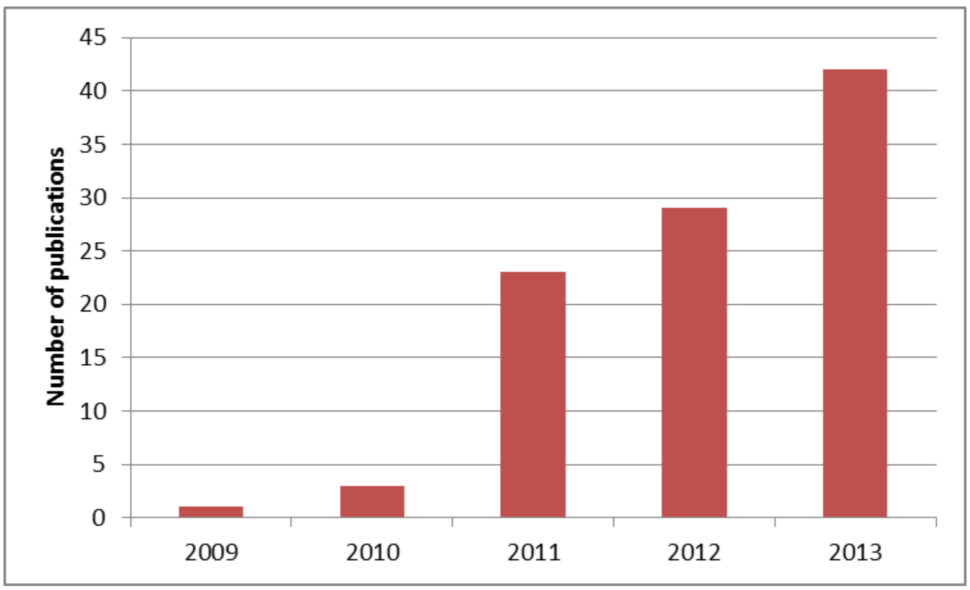

Figure 1. Number of publications on the topic of MDCs per year.

The following table summarizes the key literature findings from the last four years of MDC research.

Table 1. Summary of MDC literature findings and recommendations.

Citation	MDC Configuration	Desalination chamber Salt type / concentration	Key Findings	Recommendations for Future Work
(Cao, Huang et al. 2009)	3 chamber	NaCl, 5, 20, 35 g/L	• First literature mention of MDCs • 90% salt removal even at high concentrations over 24 hr period in batch mode	• Ferricyanide catholyte not acceptable for practice – need research on air cathode • Increasing number of chambers will increase efficiency • Develop continuous water processing
(Mehanna, Saito et al. 2010), received February 2010	3 chamber	NaCl, 5, 20 g/L	• First use of air cathode • Equal volumes of anolyte and desalination chamber solutions • Showed partial desalination; proposed MDC as pretreatment for RO • 60% reduction of saline water conductivity	• Utilize wastewater or other source of organic matter for substrate • Power generation will be increased by using wastewater with higher conductivity • Recirculation of catholyte to anode chamber to balance charge
(Mehanna, Kiely et al. 2010), received July 2010	3 chamber with added voltage (Microbial electrodialysis desalination cell, MEDC)		• Applied 0.55V using external power supply • Increased desalination capacity • Reduced saline water conductivity by 68% • Produced hydrogen gas	• Study variable applied voltage
(Jacobson, Drew et al. 2011), received March 2010	Upflow microbial desalination cell (UMDC)	NaCl, 30 g/L	• 99% NaCl removal • Saline water HRT = 4 days • Max power density = 30.8 W/m2 • 81% to 99% of electrons used for	• Optimize system for either desalination, WW treatment, or power production – operating conditions will change

			desalination process	
(Chen, Xia et al. 2011), received October 2010	Stacked microbial desalination cell (SMDC)	NaCl 20 g/L	• Total desalination rate = 0.0252 g/h	• Identify optimal number of desalination chambers
(Jacobson, Drew et al. 2011), received January 2011	Continuously-operated, UMDC	NaCl, 30 g/L	• 99% NaCl removal • Saline water HRT – 4 days • Current production = 62 mA • Power density = 30 W/m^3	• Optimize UMDC performance
(Luo, Xu et al. 2012), received November 2011	3 chamber	100 mM NaCl and 100 mM $NaHCO_3$	• 4 times higher energy production for MDC compared to MFC (microbial fuel cell w/no desalination) • Used feed with multiple ionic species rather than single solute solutions	Not mentioned
(Forrestal, Xu et al. 2012), received January 2012	3 chamber MDC compared to microbial capacitive deionization (MCDC)	10 g NaCl, 0.49 g NaH2PO4$H2O, 0.92 g Na2HPO4	• Improved performance of MCDC compared to MDC • Used additional AEM to minimize pH fluctuations caused by ion imbalances	• Improve module configuration, i.e. stacked reactors to improve diffusion and adsorption within modules • Improve operating strategies

4. Microbial desalination fuel cell research needs

Because the knowledge base for the use MDCs is still relatively small, there is a significant amount of research still needed in this area. The following is a list of potential research areas for advancing microbial desalination fuel cell technology:

- Further development on continuous flow reactors
- Optimization of multiple desalination chambers
- Anode and cathode materials and fluids
- Further testing of MDC using real water
- Develop lifecycle cost estimates for MDCs

5. References

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