Bioresource Technology 203 (2016) 280–286

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Understanding energy loss in parallelly connected microbial fuel cells: Non-Faradaic current

Junyeong An [a], Junyoung Sim [a], Yujie Feng [b], Hyung-Sool Lee [a,*]

[a] Department of Civil and Environmental Engineering, University of Waterloo, 200 University Avenue West, Waterloo, ON N2L3G1, Canada
[b] State Key Laboratory of Urban Water Resource and Environment, Harbin Institute of Technology, Harbin, China

HIGHLIGHTS

- OCV difference caused non-Faradaic current in a parallelly stacked MFC.
- Non-Faradaic current led to the energy loss in the parallelly connected MFC.
- Power reduction was only 6.7% in the parallelly stacked MFC.
- OCV should be comparable in individual MFCs for minimizing energy loss.

ARTICLE INFO

Article history:
Received 2 November 2015
Received in revised form 10 December 2015
Accepted 13 December 2015
Available online 22 December 2015

Keywords:
Parallel connection
Energy loss
Microbial fuel cell
Series connection

ABSTRACT

In this work, the mechanisms of energy loss in parallel connection of microbial fuel cells (MFCs) is explored using two MFC units producing different open circuit voltage (OCV) and current. In open circuit mode, non-Faradaic current flows in low OCV unit, implying energy loss caused by different OCVs in parallelly stacked MFCs. In a stacked MFC in parallel under close circuit mode, it is confirmed that energy loss occurs until the working voltage in high OCV unit becomes identical to the other unit having low OCV. This result indicates that different voltage between individual MFC units can cause energy loss due to both non-Faradic and Faradaic current that flow from high voltage unit to low voltage unit even in parallelly stacked MFCs.

1. Introduction

For the last past 15 years, microbial fuel cells (MFCs) have been investigated for energy-producing wastewater treatment. However, there are still some bottlenecks to be addressed for practical use, due to significant energy losses in large-scale MFCs: small voltage between donor substrate and O_2, low conductivity of wastewater, a long distance between electrodes in large reactors, maintenance of separators between electrodes, and so on (Logan and Regan, 2006; Liu et al., 2008; Logan, 2010). To minimize energy losses and increase electric power, researchers designed small MFC units connected in series or in parallel. Aelterman et al. (2006) first reported that serially stacked MFCs produced 228 W/m^3 with 2.02 V of working voltage. Several literature have also tested the stacked MFCs to improve electric power that can be used for electrical devices (e.g., pumps, sensors) (Donovan et al., 2008; Ledezma et al., 2013). One significant challenge of the serially stacked MFCs, however, is a voltage reversal phenomenon that the working voltage in the stacked MFCs becomes reversed from a positive to a negative value (Aelterman et al., 2006; Oh and Logan, 2007; An and Lee, 2014). An et al. (2015a) proved that imbalanced potentials related to different reaction kinetics on the anode or the cathode cause voltage reversal in serially stacked MFCs. Voltage reversal can seriously deteriorate or permanently stop MFC function (Oh and Logan, 2007; Kim et al., 2011). To prevent voltage reversal, Andersen et al. (2013) used capacitors and successfully controlled voltage reversal in a serially stacked MFC. Khaled et al. (2013) demonstrated an active method of balancing the voltage in a serially connected MFC, and achieved the maximum power density of ~15 $\mu W/cm^2$ in the stacked MFC without voltage reversal. An et al. (2015b) also controlled voltage reversal for a stacked MFC in series using external resistors. However, previous works have commonly shown that voltage reversal control leads to energy loss (18–20% of energy loss), while voltage reversal issues were resolved in serially stacked MFCs (An et al., 2015b); energy benefit can be negligible in the stacked MFCs when the energy loss become substantial.

---

* Corresponding author. Tel.: +1 519 888 4567x31095; fax: +1 519 888 4349.
E-mail address: hyungsool@uwaterloo.ca (H.-S. Lee).

http://dx.doi.org/10.1016/j.biortech.2015.12.033
0960-8524/

Alternatively, researchers have tested energy storage using parallel connection of MFCs to improve recovery of electrical energy from organic wastewater; primarily increasing current at consistent voltage in parallelly stacked MFCs. Hatzell et al. (2013) investigated energy efficiency of capacitors charged with parallel-connection MFCs (~0.01 Farad (F) for each unit) and powered microbial electrolysis cells to produce H_2. Kim et al. (2011) reported that energy loss in the capacitors charged with parallelly stacked MFCs was negligible. It seems that parallelly connected MFCs can be very useful for storing charges and use them in intermittent manners. However, there are no studies to characterize energy losses for the electrical circuit of parallelly stacked MFCs, although individual units of the stacked MFCs would generate different voltages or currents. The voltage of individual MFCs would not be kept constant for wastewater application, since physical, chemical, and biological properties of wastewater are fluctuated (Patil et al., 2009; Wang et al., 2011; Feng et al., 2014; An and Lee, 2014; Dhar and Lee, 2014). For instance, particulate matter in wastewater can readily lead to different anode polarization, causing different voltages in each unit of stacked MFCs (Dhar and Lee, 2014). Studies have rarely investigated the energy loss in parallelly stacked MFCs, although fundamental understanding of this energy loss is significant for moving toward large-scale MFC application to wastewater. There is no doubt that parallel connection of MFCs is very efficient to increase current capacity (An et al., 2014), but Kirchhoff's law shows that energy loss can occur even in parallelly stacked MFCs, when the voltage in individual MFC units is different each other. According to Kirchhoff's second law, the total of source voltages is identical to the sum of voltage drop in a loop. Voltage-current behavior in open circuit mode of a parallel-connected MFC, presented in Fig. 1, can be expressed with Eq. (1).

$$i \cdot R_{\text{int1}} + iR_{\text{int2}} = V_1 - V_2 \tag{1}$$

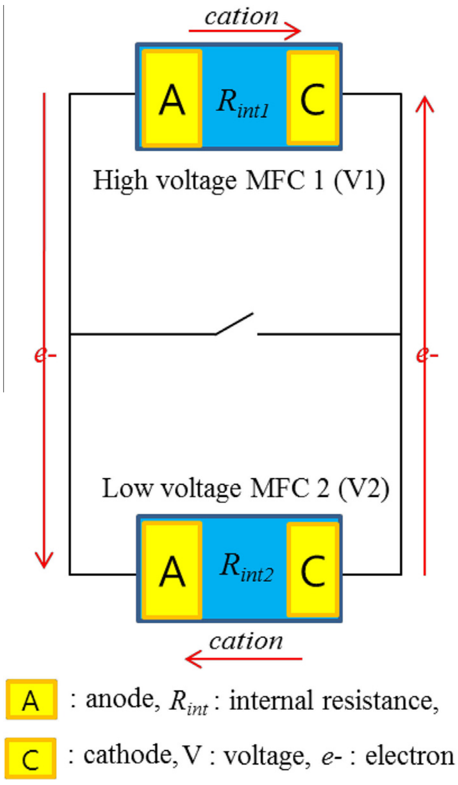

Fig. 1. A conceptual diagram of non-Faradaic current flow in open circuit mode of parallel-connected two MFC units which produce different voltage.

From Eq. (1),

$$i = (V_1 - V_2)/(R_{\text{int1}} + R_{\text{int2}}), \tag{2}$$

where i (opposite direction to electron flow) is the current (A) in the loop of Fig. 1, R_{int1} and R_{int2} are the internal resistance (Ω) in MFC 1 and MFC 2, respectively, and the V_1 and V_2 are the voltage in MFC 1 and MFC 2, respectively. Eq. (2) implies that electrical current flows in the open circuit when individual units of a parallelly connected MFC have different voltages, indicating energy loss in the stacked MFC. Energy loss for parallel connection of MFCs has been not well understood, although characterization and quantification of energy loss in parallel connection of MFCs are of significance for practical application in large scale. In this study, to better comprehend the energy loss in parallelly connected MFCs, we intentionally prepared two identical MFCs having different voltages and explored the mechanism for the energy loss. First, a parallelly connected MFC was tested to understand energy loss, given that different voltages of individual units in the stacked MFC can cause energy loss in the circuit. Two MFC units producing different voltages were connected in parallel to prove the hypothesis. Then, the occurrence of energy loss was assessed in open circuit and closed circuit mode of the parallelly stacked MFC. Herein we proved that voltage in individual MFC units should be close to minimize energy loss in parallelly stacked MFCs.

2. Methods

2.1. Assembly of microbial fuel cells (MFCs)

Pyrex glass was used to fabricate two identical single-chambered MFCs (MFC 1 and 2). The working volume of each anode chamber was 29 mL. Carbon fiber (2293-A, 24A Carbon Fiber, Fibre Glast Development Corp., Ohio, USA) was employed as the anode, and platinized gas diffusion carbon cloth (0.3 mg/cm^2 with 40% Pt/C; CCP40, Fuel Cell Earth, USA) was used for the cathode (air-cathode) in the MFCs. Nafion membrane (PEM, Nafion 212, Dupont Co., USA) was sandwiched between the electrodes as separator, and the projected area of the membrane was 9.6 cm^2. A rubber gasket was positioned between the cathode and an outer frame to prevent liquid leakage. An Ag/AgCl reference electrode (BAS, MF-2052, USA) was equipped on the top of the anode chamber at ~2 mm apart from the anode in order to monitor anode potential. In this work, we designated individual MFC units that are not connected in parallel as n-Unit 1 and n-Unit 2. Individual MFCs were called p-Unit 1 and p-Unit 2 when they are connected in parallel. p-MFC indicates the stacked MFC in parallel consisting of p-Unit 1 and p-Unit 2.

2.2. Acclimation and enrichment of anode respiring bacteria (ARB)

To acclimate anode-respiring bacteria (ARB) on the anode, 29 mL of recycle activated sludge sampled from a domestic wastewater treatment plant (Waterloo, ON, Canada) was inoculated into each anode chamber of the MFCs. Air was passively supplied to the air-cathode. Then, an external resistor of 120 Ω was applied between the anode and the cathode (An and Lee, 2014; An et al., 2015a,b). After closed circuit voltage (CCV) was stabilized at ~4.2 mV in the MFCs run in batch mode with acetate medium (25 mM acetate amended with 50 mM of phosphate buffer), the MFCs was operated in continuous mode using a peristaltic pump (Masterflex, Model 7523-80, USA) at a hydraulic retention time (HRT) of ~2.5 h. The pH in the anode was constant at 7.3 ± 0.2 during experiments. After long-term operation over ~6 months, the current in the MFC 1 and 2 was stabilized at ~0.21 and 0.24 mA/cm^2 (2.0 and 2.3 mA), respectively.