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# Series and parallel connection of anaerobic fluidized bed microbial fuel cells (MFCs)

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## ABSTRACT

**The effects of the connection manner of anaerobic fluidized bed microbial fuel cells (MFCs) on the properties of electricity generation and sewage treatment were investigated in the liquid-solid fluidized bed single-chamber membrane air-cathode fuel cells (0.032 m in diameter, 0.6 m in height). In addition, the effects of electrode area, filling volume of activated carbon and temperature on electricity generation were studied. The results obtained show that the maximum open circuit voltage (OCV) of serially connected stack MFC (three microbial fuel cells) was about 2100 mV equivalents to the sum of the individual MFCs. The maximum power of the series MFCs and the single fuel cell were 0.12 and 0.05 mW, respectively. In parallel, the maximum total OCV was 800 mV, corresponding to the maximum current of 0.3 mA. Moreover, the maximum OCV increased by 78% when anode area increasing from 17 to 68 cm$^2$. The electricity generation could be increased with increasing filling volume of activated carbon. The maximum OCV and the minimum resistance of the MFCs series both observed at 40°C. And the chemical oxygen demand (COD) of simulated wastewater decreased to 31.75 from 3859 mg/L after running 4 days in this MFCs system.**

## INTRODUCTION

Currently, environmental pollution and resource shortage have directly affected human life and development. It is necessary to develop sustainable energy technologies that can promote the world's future economic development. Nowadays wastewater treatment has become a hot topic in environmental problem. Microbial fuel cell (MFC) uses microorganisms to oxidize organic or inorganic matter and directly convert chemical energy into electrical energy (Reddy et al., 2010).There are plenty of organics in industrial wastewater. MFC has emerged as a promising technology because of its ability to simultaneously treat wastewater and accomplish power generation. In recent years, MFC technology for wastewater treatment and electricity production is still a new and challenging field in the world due to its effectiveness and potential application. Anaerobic fluidized bed microbial fuel cell is the coupling of the microbial fuel cell technology with the fluidized bed reactor. The power density and voltages can be increased when MFCs are stacked in series or in parallel. Individual MFC and electrode material have been widely investigated in the world (Park et al., 2012; Cai et al., 2013; Pandit et al., 2012; Martin et al., 2013). The high cost and low voltage has been hampering a systematic scale up of MFC. In order to reduce costs of MFC, Cheng et al. (2006) have shown that the cathode catalyst Pt can be reduced to 0.1 mg/cm$^2$. In addition, it has been found that the MFC performance is influenced by many operational parameters, such as temperature (Jadhav and Ghangrekar, 2009; Campo et al., 2013), pH (Puig et al., 2010), substrate concentration (Nam et al., 2010a; Nam et al., 2010b) and electrode distance (Raman and Lan, 2012). A new cell configuration, cloth

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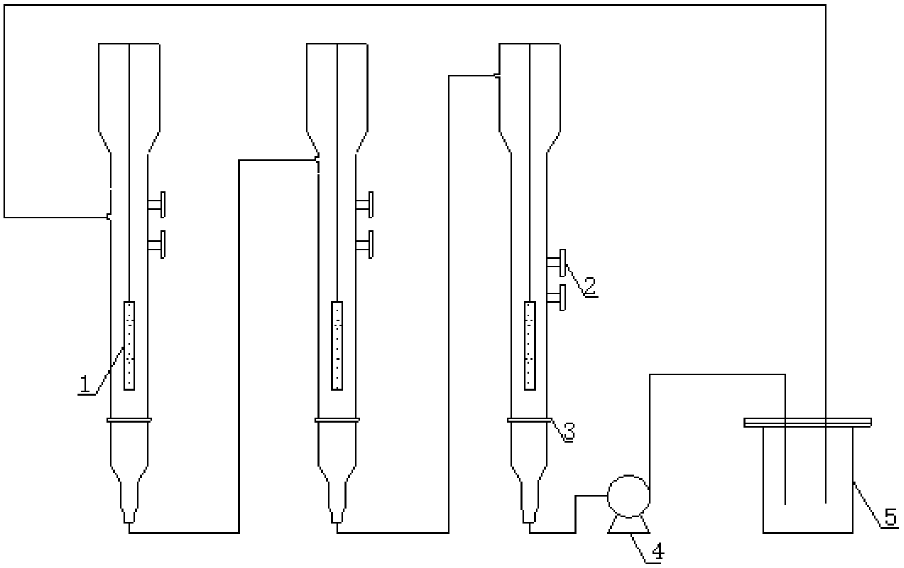

**Figure 1.** The schematic of anaerobic fluidized bed microbial fuel cells. 1) A carbon rod anode; 2) carbon cloth cathode; 3) distribution board; 4) a peristaltic pump; 5) water storage tank.

electrode assembly (CEA), was designed by sandwiching the cloth between the anode and the cathode. Such an MFC configuration greatly reduced the internal resistance, resulting in a power density of 627 $Wm^{-3}$ when operated in fed-batch mode and 1010 $Wm^{-3}$ in continuous-flow mode, which is the highest reported power density for MFCs and more than 15 times higher than those reported for air-cathode MFCs using similar electrode materials (Fan et al., 2007). The scale of MFC system must be increased to meet the requirements for large-scale wastewater treatment and bioelectricity production. Capital cost, scalability, modularity and distribution system for MFCs are the most crucial issue. One approach for scale-up is to increase the size of an individual MFC unit (Liang et al., 2009; Zhang et al., 2010). However, it was reported that the maximum voltage of an air-cathode MFC did not exceed 1.1 V. MFC scale-up may be more successful when connecting a number of single units together rather than increasing the size of an individual unit (Ieropoulos et al., 2008). Thus, the strategy of stack system has been used in MFCs for increasing the power output (Dekker et al., 2009; Zhuang et al., 2012; Kim et al., 2011). In 2006, Aelterman et al. (2006) showed that one possible way of achieving higher power output from MFCs is connecting multiple small-sized units together either in series or in parallel. But, in that time, the effect on the microbial electricity generation was as yet unknown. In 2008, Ieropoulos et al. (2008) found that based on measured power output from 10 small units; a theoretical projection for 80 small units is approximately 50 times higher than the single MFC.

In recent years, the research on anaerobic fluidized bed MFC has attracted a great deal of interests. Most studies were based on single anaerobic fluidized bed MFC. Zhao et al. (2010) treated the artificial wastewater in single anaerobic fluidized bed MFC, the chemical oxygen demand (COD) removal ratio was 85% after running 4 days. Kong et al. (2011) treated sanitary wastewater in individual anaerobic fluidized bed MFC, the COD removal ratio was 91% after running 10 days. But no studies have been published treating wastewater using series or parallel anaerobic fluidized bed MFCs. In this work, three anaerobic fluidized beds were in series to achieve a continuous flow of wastewater that can be kept adequate substrate. Thus, the voltage reversal phenomenon was avoided successfully. The performance of electricity generation and wastewater treatment were investigated when MFCs were stacked in series or parallel in different conditions. It can provide basic data for the industrial application of anaerobic fluidized bed microbial fuel cells.

## MATERIALS AND METHODS

### Anaerobic fluidized bed microbial fuel cells

The reactors were fabricated with Plexiglas (0.032 m in diameter, 0.6 m in height, the effective volume is 1280 mL). They were consisted of three individual MFC units (Figure 1). Influents were fed into MFCs through peristaltic pumps from the bottom of the first fluidized bed and overflow from the top of the bed. The overflow outlet of last two fluidized beds was lower than the previous in order to promote fluidization. The cathode was carbon cloth which was covered with Pt/C catalyst. Anode was consisted of carbon rod to collect the electrons (7 mm in diameter, 150 mm in length). MFCs were connected in series or parallel using copper wires.

### Microorganism and wastewater

Sludge was collected from the Licun river wastewater treatment plant in Qing Dao. It was incubated at 30°C in a constant-temperature room for three months. The medium was added in nutrient mineral consisted of 1 g/L glucose, 1 g/L yeast extract fermentation (YEF), 0.123 g/L $CaCl_2$, 0.31 g/L NaCl, 1.3 g/L K2HPO4, 0.23 g/L $NH_4Cl$, 0.33 g/L KCl, 0.315 g/LMgCl2, 0.42 g/L $KH_2PO_4$. Wastewater was simulated wastewater which has the same constituent as nutrient mineral (Zhao et al., 2010).

### Measurement methods

Anode and cathode were connected to the external circuit using copper wires. The wire was connected to a resistor and a data collection instrument (model USB-1608FS) in succession and the data were stored in a computer. When “U” is the potential drop across the electrical resistor (R equiv), “I” is the current passing through the resistor, “P” is power, “S” is cathode area, the current and power density are calculated as;

$$I = \frac{U}{R} \quad (1)$$

$$P = \frac{UI}{S} = \frac{U^2}{RS} \quad (2)$$

COD is an indicator of the content of organic matter in water. Oxidizing abilities of the COD (Cr) method use $K_2Cr_2O_7$ .When “$V_0$” is the volume of water,“$V_1$” is the volume of $(NH_4)_2Fe(SO_4)_2$ in the blank test, “$V_2$” is the volume of $(NH_4)_2Fe(SO_4)_2$ in water determine, “C” is concentration of $(NH_4)_2Fe(SO_4)_2$ ,the COD is calculated as:

$$COD_{cr}=(V_1-V_2)\cdot C\cdot 8\times 1000/V_0 \quad (3)$$

### MFC Startup and Operation

In fact, MFC startup is the growth of anaerobic bacteria to form biofilm. The anode chamber was inoculated with 10 mL microorganism. The MFCs were connected with the silicon tubing and wire. MFC tests were operated at a fixed external circuit resistance (90000 Ω). In the MFCs startup the flow rate of wastewater is 2 mm/s. The wastewater is kept at a constant temperature of 40°C. Microorganism in the fuel cells requires an adaptation process and the biofilm formation on the surface of the anode needs a period. Therefore, anaerobic fluidized bed microbial fuel cells startup require long time. At the beginning of startup, the OCV of single MFC and series MFCs were 450 and 1350 mV, respectively. After 48 hours, the OCV maximum (2100 mV) of series MFCs was appeared, and OCV maximum (800 mV) of parallel MFCs was same with single MFC (Figure 2).

## RESULTS AND DISCUSSION

### Series connection: OCV and power

In the stable operation of the MFCs, the single MFC OCVs were 700, 820 and 680 mV, respectively. When they were stacked together in series, the maximum output OCV was 2100 mV, which was equal to the sum of three individual batteries (Figure 3a). The series MFCs could run successfully without voltage reversals. Gurung et al. (2012) also mentioned that voltage reversal can be discovered in series. In series of fuel cells system, protons can be generated from electron reaction in different batteries. But electrons and protons number could be various in different cell, therefore the electrode potential could be various. When cathode potential decreased and anode potential increased at same time, the voltage reversal would be appeared.In series of MFCs, circuit voltage reversal is a common phenomenon, but which did not occur in the present study. The reason is that air-cathode can offer sufficient oxygen in the cathode and simulated wastewater has sufficient organic substrate. Therefore, the difference of electrode potential was avoided between different single MFC. The maximum power of MFCs series was 0.12 mW and maximum power density was 11.7 $mW/m^2$, the corresponding values of the single fuel cell were 0.05 mW and 14.7 $mW/m^2$. The internal resistance can be obtained from the curve of voltage and current. The internal resistance was 10000 Ω in series, corresponding to 3000 Ω in the single fuel cell. The reasons for internal resistance are as follows: First, the carbon is a poor conductor and is not connected tightly enough with the anode and wire, which influences electron transfer. Second, internal resistance will be increased with the distance between anode and cathode increasing (Gurung et al., 2012).

### Parallel connection: OCV and power

In the stable operation of the microbial fuel cell, the

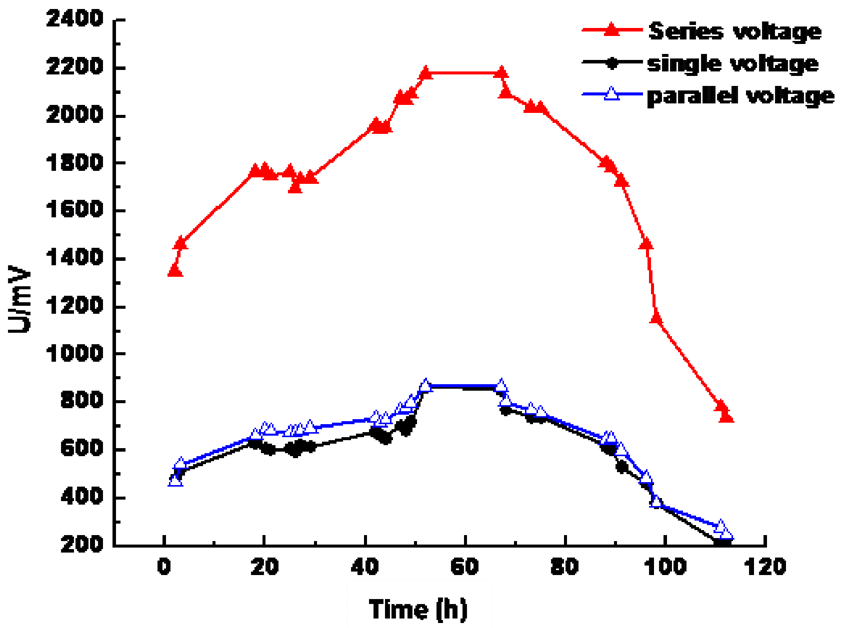

**Figure 2.**OCV of MFCs in different time at 40°C.

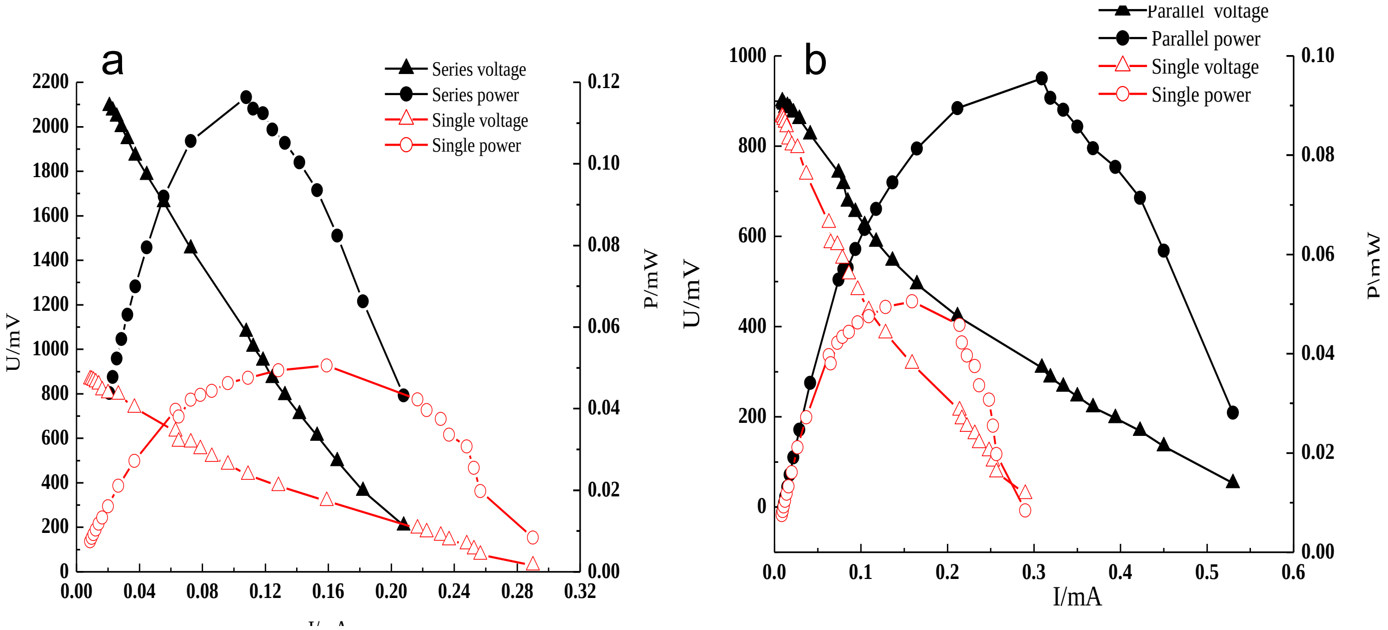

**Figure 3.**Effects of connection manner on properties of electricity generation at 40°C.a) Polarization curves in series and single MFC; b) Polarization curves in parallel and single MFC.

maximum OCVs of three single MFCs were 700, 820 and 680 mV, respectively. When they were stacked together in parallel, the maximum OCV was 800 mV, which approximates to the voltage of single MFC. Aelterman et al. (2006) has studied the stack MFCs by six cells in parallel. It was also found that the maximum voltage of parallel MFCs was 668 mV, and the corresponding value of single MFC was 693. The results showed that parallel MFCs could not increase the output voltage in this work (Figure 3b). The maximum power of parallel MFCs was

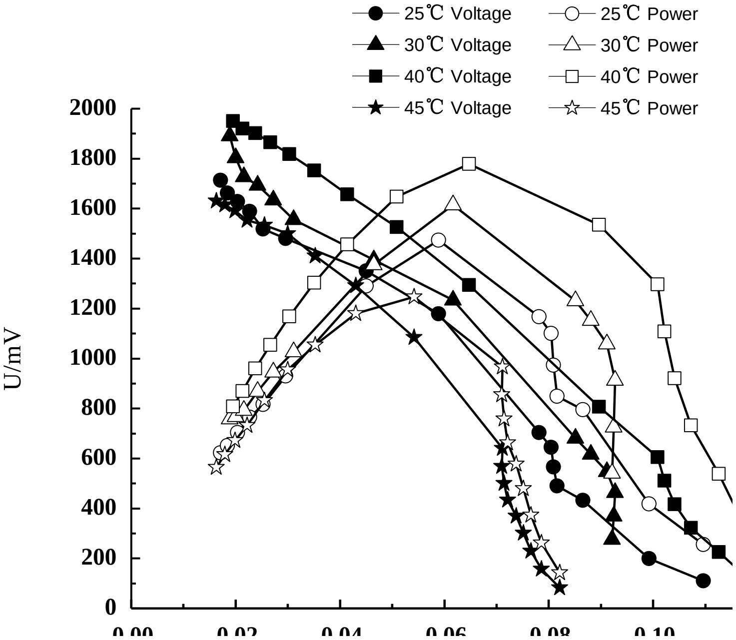

**Figure 4.** Effects of temperature on properties of electricity generation (in series connection).

**Table 1.** Relationship between temperature and electricity generation properties.

| Temperature (°C) | Relationship | Resistance (Ω) |
|---|---|---|
| 25 | U=2019-17589I ($R^2$=0.9821) | 17590 |
| 30 | U=2139-16977I ($R^2$=0.9849) | 16980 |
| 40 | U=2311-16512I ($R^2$=0.9942) | 16510 |
| 45 | U=1998-18605I ($R^2$=0.9674) | 18610 |

0.09 mW, and the corresponding value of the single MFC was 0.05 mW. Power density of parallel MFCs was 8.9 mW/$m^2$, while the corresponding value of the single MFC was 14.7 mW/$m^2$. However, the internal resistance of parallel MFCs was 1700 Ω, which was far less than the single MFC (3000 Ω) and series MFCs (10000 Ω). Therefore, the maximum current of MFCs in parallel was 0.3 mA when the power was the highest, which was much higher than single MFC or MFCs series.

## Effect of reaction temperature on properties of electricity generation in series connection

The effect of reaction temperature on the OCV is remarkable in the practical application of MFCs. Ratledge et al. (2006) mentioned that the suitable reaction temperature of MFC is 20-45°C. The reaction temperature in the series MFCs was increased from 25 to 45°C. The results are shown in Figure 4. The OCV was enhanced and then decreased with the ascent of reaction temperature. The OCV and the power of the MFCs both reached a maximum at 40°C. In Figure 4, voltage (U) and electric current (I) also presents a linear trend: U=λ-IR ("R" is resistance).The linear fitting equations are shown in Table 1: resistance was decreased and then increased there after with the increasing temperature and the minimum resistance appeared at 40°C. Therefore, the feasible reaction temperature of the present MFCs is 40°C.

## Effects of cathode and anode areas on OCV

The relative sizes of the anode and cathodes can affect output power. Oh et al. (2006) mentioned that the power output was proportional to cathode surface area when the

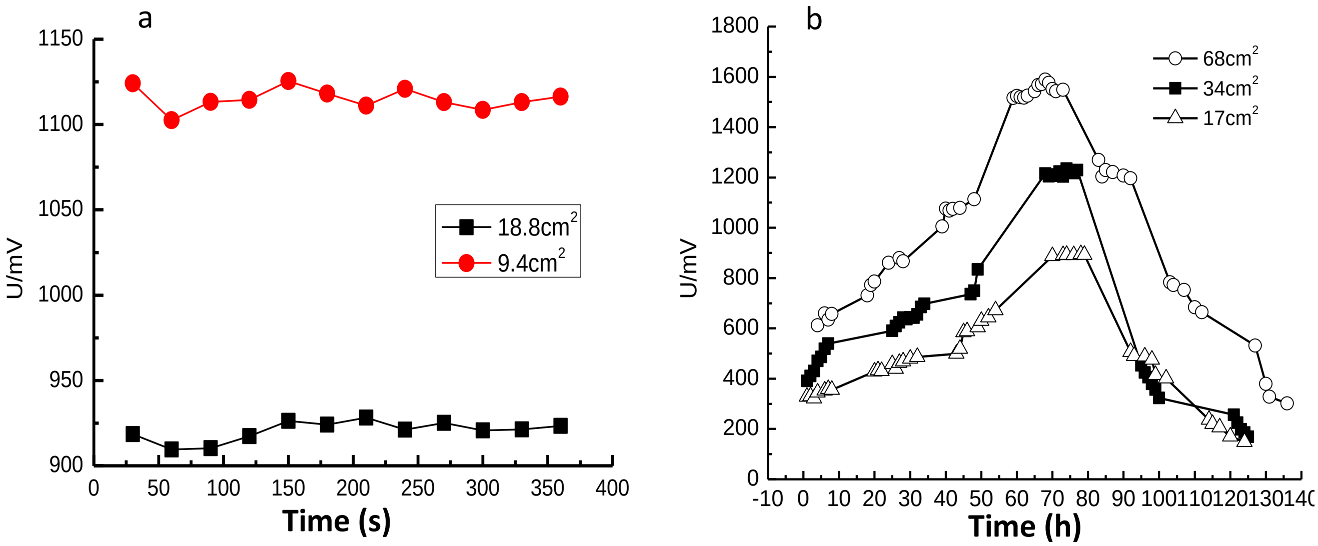

**Figure 5.** Effects of electrode area on OCV. a) OCV change with different cathode area; b) OCV change with different anode area.

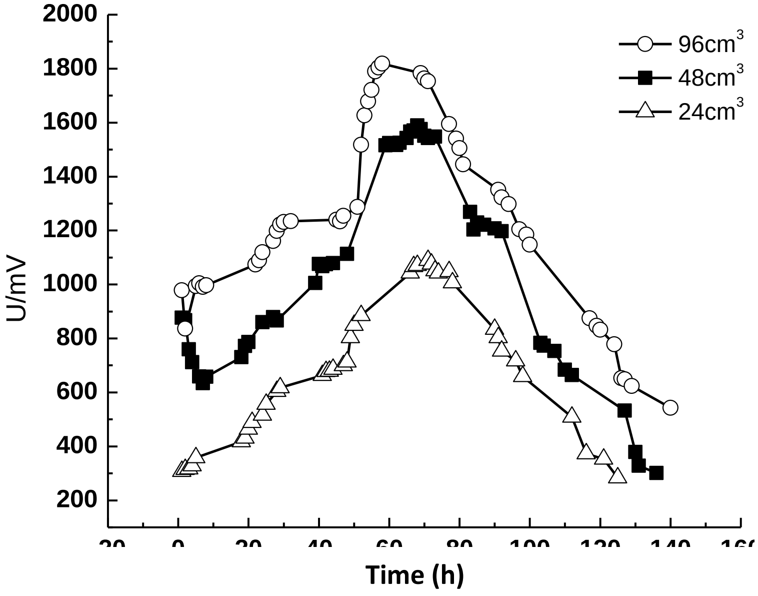

**Figure 6.** Effects of activated carbon filling volume on OCV.

PEM is of a sufficient size for the system. In this study, the maximum OCV increased by 20% when the cathode area increased from 9.4-18.8 cm$^2$ (Figure 5a). And the output power increased from 9 mW up to 14 mW.

The anode was the carrier of microorganism and it attended oxidation reaction at the same time. Therefore, the size of anode affects not only the microorganism amount on the anode but also the electrons transfer in the system (Oh et al., 2006). In this work, the maximum OCV increased by 78% when anode area increased from 17-68 cm$^2$ (Figure 5b).

## Effects of activated carbon filling volume on the properties of electricity generation

Figure 6 described the effects of activated carbon filling volume on the properties of electricity generation. When

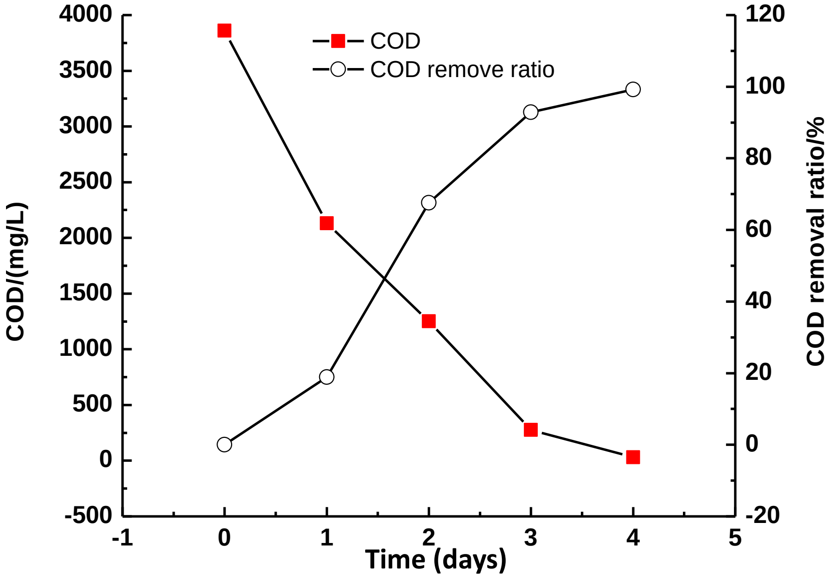

**Figure 7.**COD and COD removal ratio in different time.

the filling volume of activated carbon increased from 24-96 cm$^3$, the maximum OCV was increased from 1089 mV up to 1818 mV. At the same time, the running time which reaching maximum OCV was decreased by 13 h. This is because that the contact time between wastewater and anaerobic adsorbing with activated carbon increased with activated carbon filling volume increasing.

## COD of wastewater and COD removal ratio

Besides electricity generation, COD removal ratio is another important parameter to evaluate MFCs. The COD and COD removal ratio of the wastewater are shown in Figure 7. The results showed that the COD of wastewater was decreased with the prolongation of running time, while the variation trend of the COD removal ratio was contrary. The COD of simulated wastewater was decreased from 3859 mg/L to 31.75 mg/L after running 4 days in this system, and the COD removal ratio was up to 99%. Zhao et al. (2010) treated the simulated wastewater with the same composition as this work in single MFC, the COD removal ratio was 85% after running 4 days. Therefore, the treatment efficiency of three stage MFCs was greater than single MFC.

## Conclusion

The OCV of three MFCs series was equal to the total of the three individual MFCs, and voltage reversal did not occur in the present study. The MFCs series ran for 20 h stably at the maximum OCV of 2100 mV. The maximum power of MFCs series was 0.12 mW and power density was 11.7 mW/m$^2$, the corresponding values of the single fuel cell were 0.05 mW and 14.7 mW/m$^2$, respectively.

Parallel MFCs could not increase the OCV. However, the internal resistance of parallel MFCs was 1700 Ω, which was far less than the single MFC (3000 Ω) and series MFCs (10000 Ω). The maximum current of MFCs in parallel was 0.3 mA when the power was the highest, which was much higher than single MFC or series MFCs.

The COD of simulated wastewater was decreased from 3859 mg/L to 31.75 mg/L after running 4 days. The treatment efficiency of three stages MFCs was greater than single MFC.

## ACKNOWLEDGEMENTS

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