

# Effect of operating modes on simultaneous anaerobic sulfide and nitrate removal in microbial fuel cell

Jing Cai · Ping Zheng · Mahmood Qaisar · Yajuan Xing

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**Abstract** The effect of operating modes on the simultaneous sulfide and nitrate removal were studied in two-chamber microbial fuel cells (MFCs). The batch and continuous operating modes were compared and evaluated in terms of substrate removal and electricity generation. Upon gradual increase in the influent sulfide concentration from 60 to 1,020 S mg L<sup>-1</sup>, and the hydraulic retention time decrease from 17.2 to 6 h, the MFC accomplished a good substrate removal efficiency whereby nitrogen and sulfate were the main end products. The removal efficiency of the MFC in the continuous mode was much higher than that in the batch mode, and its current densities in the continuous mode were more stable and higher than in the batch mode, which could be explained by the linear relationship between electrons released by the substrates and accepted on the electrodes. The electricity output in the continuous mode of the MFC was higher than that in the batch mode. MFC's operation in the continuous mode was a better strategy for the simultaneous treatment of sulfide and nitrate.

**Keywords** Microbial fuel cell · Anaerobic sulfide and nitrate removal · Batch mode · Continuous mode

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J. Cai (✉)  
College of Environmental Science and Engineering, Zhejiang  
Gongshang University, Hangzhou 310012, China  
e-mail: caijing@zju.edu.cn

P. Zheng (✉) · Y. Xing  
Department of Environmental Engineering, Zhejiang University,  
866 Yuhangtang Road, Hangzhou 310058, Zhejiang, China  
e-mail: pzheng@zju.edu.cn

M. Qaisar  
Department of Environmental Sciences, COMSATS Institute  
of Information Technology, Abbottabad, Pakistan

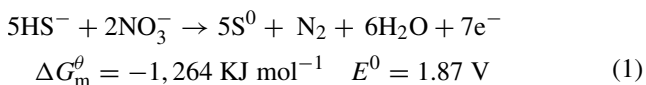
## Introduction

An increasing trend in world energy consumption has been recorded recently [17]. The world is facing a severe energy shortage at present. Traditional wastewater treatment consumes a large amount of the electric supply. For instance, aeration during sewage treatment demands about 0.5 kWh m<sup>-3</sup> of the power supply, which accounts for energy use of 30 kWh per capita per year [1]. The balance between energy consumption and pollution control is a great concern in the field of environmental engineering.

Microbial fuel cells (MFCs) represent an innovation in the field of wastewater treatment, which can generate electricity during the degradation of substrates [14]. The concept was explored as early as 1911, and microbial fuel cells treating domestic wastewater were presented in 1991 [9]. The treatment of pollutants in the wastewater is no longer the object alone, but it is regarded as an energy source now. The study of MFCs is gaining popularity now. Most of the studies have been based on organic wastewater containing glucose, acetate, sucrose, etc. [18], and only a few studies have considered inorganic wastewaters (such as sulfide-containing waste streams).

Sulfide-containing waste streams are generated by many industries, such as petrochemical plants, tanneries, viscose rayon factories, etc. [15]. Sulfide is toxic, odorous and corrosive, and its various toxicological effects on human health have been described elsewhere [10]. Sulfide treatment is accomplished by physical, chemical and biological processes [20]. The biological processes are cost effective because they operate in natural ambient conditions without any requirement of expensive chemicals and catalysts [6]. Some bacterial species can oxidize sulfide to elemental sulfur with the simultaneous reduction of nitrate or nitrite to dinitrogen [8]. Hence, nitrate can be used to control

the sulfide generation under anoxic or anaerobic conditions. For such reasons, the simultaneous anaerobic sulfide and nitrate removal process has been recently developed (Eq. 1).



Based on theoretical calculation, the simultaneous anaerobic sulfide and nitrate removal can be accomplished in MFCs (Eq. 1). So far, however, few studies have reported this process in MFCs. Lee et al. [13] studied the interactions between denitrifying sulfide removal (DSR) and the MFC processes and confirmed that the MFC was capable of the simultaneous sulfide and nitrate removal using a single culture of *Pseudomonas* sp. C27. Our research group has operated a two-chambered MFC for simultaneous anaerobic sulfide and nitrate removal. Based on the cyclic voltammetry (CV) curves and the balance of the released and accepted electrons, it was concluded that the electricity generation was coupled with the substrate conversion in MFC [3, 4].

Most studies involving MFCs were conducted in the batch mode [14]. However, several disadvantages are also associated with the batch-mode process such as substrate depletion in view of limited nutrients and toxicity of its by-products [19]. The process in continuous mode is suitable for its practical applications such as power production and wastewater treatment [5]. Therefore, two common operating modes (continuous and batch) were investigated to explore the simultaneous sulfide and nitrate removal in MFCs using activated sludge. The specific objective was to compare the effect of operating modes on the substrate removal and power generation in MFCs, which could lay the foundation for improvement of the design of MFCs.

## Materials and methods

### Inoculum and enrichment of microbial communities

The inoculum was collected from the anaerobic methanogenic reactor operated at Dengta wastewater treatment plant (WWTP) located in Hangzhou City, China. Its total solids (TS) and volatile suspended solids (VSS) were 95.03 and 68.68 g L<sup>-1</sup>, respectively, with a VSS:TS ratio of 0.72. The reactor accomplishing simultaneous anaerobic sulfide and nitrate removal operated under lithoautotrophic conditions where sulfide was used as electron donor and nitrate was employed as electron acceptor. For the initial 1 month, the reactor was fed with synthetic wastewater in order to acclimatize the microbial species to the new substrates and to enrich the functional bacterial populations.

### Synthetic wastewater

The MFC was fed with the synthetic influent containing NaHCO<sub>3</sub>, MgCl<sub>2</sub>, KH<sub>2</sub>PO<sub>4</sub>, (1 g L<sup>-1</sup> each), (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> (0.24 g L<sup>-1</sup>) and trace element solution (1 mL L<sup>-1</sup>). The trace element solution was prepared according to Mahmood et al. [16]. The nitrate-nitrogen and sulfide-sulfur concentrations were administered as potassium nitrate (KNO<sub>3</sub>) and sodium sulfide (Na<sub>2</sub>S·9H<sub>2</sub>O), respectively; their concentrations were controlled according to the requirements of the experiment conducted.

### MFC construction

The MFC consisted of anode and cathode chambers; both had the capacity to accommodate a total volume of 350 mL (300 mL net volume), which was reported in our previous study [3]. The electrodes were connected by a cation exchange membrane (CEM) (Ultrax CMI-7000 Membrane International, USA). The electrodes were graphite felt (6 × 3 cm, 36 cm<sup>2</sup> net superficial area); they were placed at the center of each chamber and were parallel to the CEM. An external resistance of 1,000 Ω was applied to control electron flow between the electrodes. Activated sludge (100 mL) was inoculated in an anode chamber, and the solution in anodic chamber was circulated by a peristaltic pump. The cathode medium was a mixture of 50 mM PBS buffer (pH 7.0) and 100 mg L<sup>-1</sup> potassium permanganate (KMnO<sub>4</sub>), which was circulated and recycled over the cathode compartment using a 2.5-L external buffer vessel by peristaltic pumps.

### MFC operation

Two MFCs of same configuration were used in the experiment. One was operated in continuous mode, and the other was operated in batch mode; both were operated at room temperature.

When the MFC was operated in batch mode, the synthetic wastewater was fed to the anode chamber daily, whose volume was 200 mL. Sulfide was added to a final concentration of 60 mg L<sup>-1</sup> after the anodic chamber had been flushed with N<sub>2</sub> for 5 min to remove O<sub>2</sub> in the solution. The nitrate concentration was increased according to stoichiometry of the chemical reaction (with an S:N molar ratio of 5:2) given in Eq. 1. The MFC was operated under the circumstances until the effluent quality turned stable. Then the influent substrate concentrations were increased to the next level. In the experiment, five concentrations were studied: 60, 300, 540, 780 and 1,020 mg S L<sup>-1</sup>, respectively.

When the MFC was operated in continuous mode, the synthetic wastewater was fed to the system by a peristaltic pump. Keeping the influent substrate concentrations

constant (300 mg S L<sup>-1</sup> and 52.5 mg N L<sup>-1</sup>, respectively), the volumetric loading rate was raised by decreasing the hydraulic retention times (HRTs). In the experiment, five HRTs were studied (17.2, 13.8, 10.6, 8 and 6 h, respectively). The influent pH was maintained at 7.0 ± 0.1 throughout the experiment.

The effluent substrate concentrations were analyzed every 22 h after the injection of the influent solution.

Analytical procedures

The influent and effluent nitrate-nitrogen, pH and sulfide were analyzed during the operation of the MFC. Nitrate-nitrogen (NO<sub>3</sub><sup>-</sup>-N) was analyzed by an ultraviolet spectrophotometric screening method on a daily basis using a spectrophotometer (Unico UV-2102 PC and 722S, China) [2]. The sulfide was determined by an iodometric method, and sulfate was measured using a turbidimetric method [2]. The pH was determined following the standard method [2]. A three-point calibration of the pH meter was performed on a daily basis. The total solid (TS) concentration was determined according to the gravimetric method at 103 °C, and volatile solids were analyzed using the gravimetric method at 550 °C [2].

Voltage across the 1,000 Ω resistor was recorded at an interval of every 1 min using a digital acquisition system (Agilent 34970A Data Acquisition/Switch Unit). Current density was normalized by the net surface areas of the anode electrode.

According to Eq. (2), the electrons were represented by the area under the voltage curve.

$$Q = It = Ut/R \tag{2}$$

where *Q* represents the quantity of electricity (C); *I* is the current (A); *t* represents time (t); *U* is the voltage (V); *R* represents the resistance (Ω).

Results

The performance of the MFC in batch operating mode

During the gradual increase in the influent sulfide concentration from 60 to 1,020 mg S L<sup>-1</sup>, the sulfide removal percentage was higher than 99.5 %, with an effluent concentration of <1.2 mg S L<sup>-1</sup> (Fig. 1). The effluent sulfate concentration rose with the increase in influent sulfide, which was increased from 15.06 to 659.70 mg S L<sup>-1</sup>.

As the influent nitrate concentration was elevated from 12.10 to 178.50 mg N L<sup>-1</sup>, the concentrations of nitrate and nitrite in the effluent gradually increased from 0.01 and 0.25 to 2.22 and 5.61 mg N L<sup>-1</sup>, respectively, and the nitrate removal percentage went down to 98.76 %.

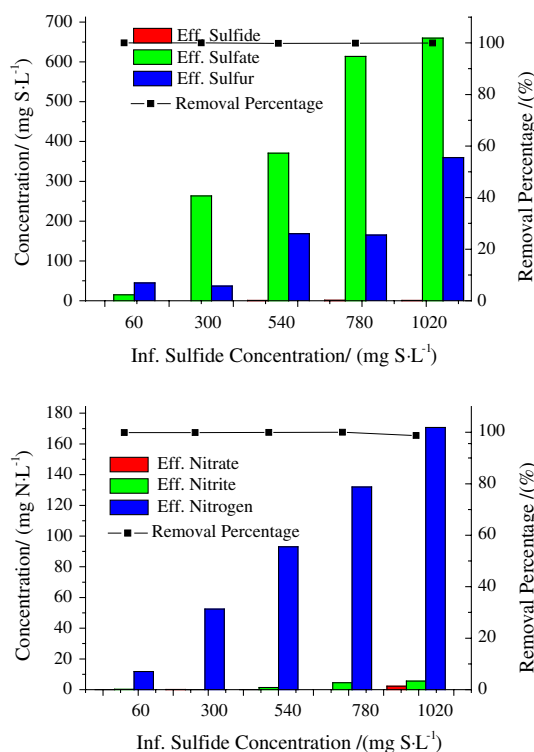


Fig. 1 Substrate removal of the MFC in batch operating mode

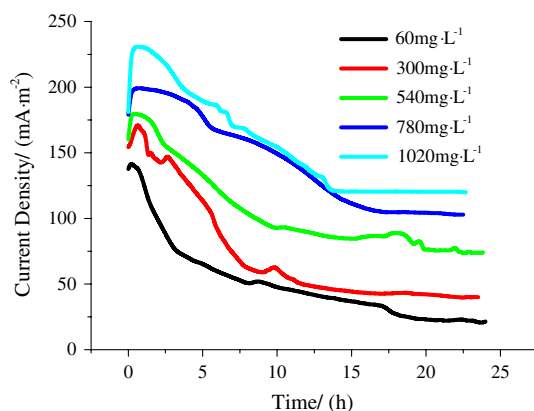


Fig. 2 Electricity generation of the MFC in batch operating mode

Feeding 1,020 mg S L<sup>-1</sup> in the influent, the removal percentages were higher than 95 % during the batch mode of the MFC. However, the effluent pH value fell to 6.10 ± 0.1 causing the process instability.

At the external resistance of 1,000 Ω, the maximum current density of the MFC was 142 mA m<sup>-2</sup> during the first 10 min when fed with 12.12 mg N L<sup>-1</sup> nitrate and 60 mg S L<sup>-1</sup> sulfide (Fig. 2). But subsequently it decreased sharply and dropped to 78 mA m<sup>-2</sup> in the 3rd hour (decreased by 44.7 %). It further descended slowly to about 34 mA m<sup>-2</sup> in the 17th hour. In the end, it reached

the lowest point ( $23 \text{ mA m}^{-2}$ ). The profiles of current density were similar at different influent concentrations, and the current density had a linear relationship with the influent substrate concentrations, and its maximum value was  $231 \text{ mA m}^{-2}$  in the experiment. However, the maximum value appeared in the beginning and lasted for a short time. After reaching its maximum, the current density decreased rapidly, and it dropped to a relatively stable value which lasted for more than 10 h. The current density fluctuated slightly in that period. The value of current density in 22 h was considered as the steady voltage. When the influent sulfide concentration is elevated to  $1,020 \text{ mg S L}^{-1}$ , the steady current density increases to  $120 \text{ mA m}^{-2}$  (the highest in the tested concentration range).

The performance of the MFC in continuous operating mode

Keeping the influent substrate concentrations constant ( $300 \text{ mg S L}^{-1}$  and  $52.5 \text{ mg N L}^{-1}$ , respectively), the HRT was decreased from 17.2 to 6 h. Consequently, the effluent sulfide concentration reached  $4.15 \text{ mg S L}^{-1}$ , with the sulfide removal percentage higher than 97.2 % (Fig. 3). The effluent sulfate concentration ranged from 187.44 to  $283.08 \text{ mg S L}^{-1}$  with decreasing HRTs.

For an HRT decrease from 17.2 to 6 h, the effluent nitrate and nitrite concentrations increased from 0.48 and 0.63 to 3.75 and  $2.92 \text{ mg N L}^{-1}$ , which lowered the nitrate removal percentage to 87.3 %.

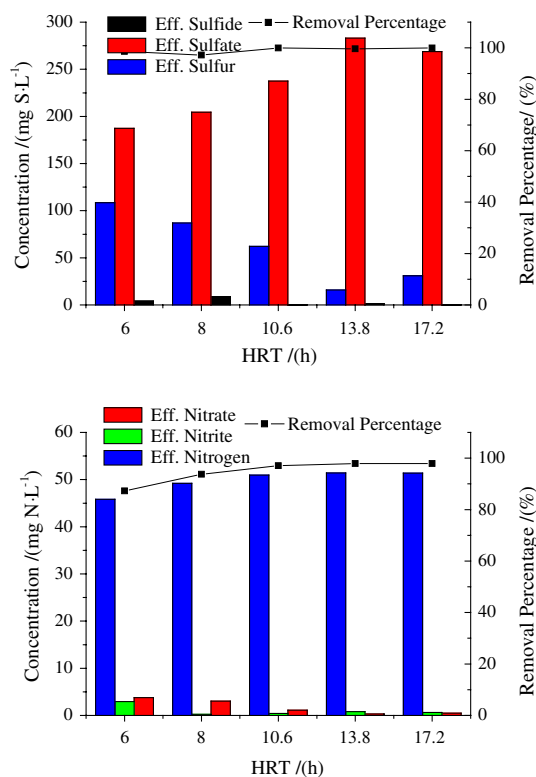
At an HRT of 6 h, the substrate removal percentages in batch operating mode were higher than 87 %. However, it was accompanied by a great loss of activated sludge, and the reactor hardly sustained working.

Under the external resistance of  $1,000 \Omega$  and HRT of 17.2 h, the current density of the MFC was stable (in the range of  $86\text{--}102 \text{ mA m}^{-2}$ ) when fed with  $52.5 \text{ mg N L}^{-1}$  nitrate and  $300 \text{ mg S L}^{-1}$  sulfide (Fig. 4). The profiles of current density were similar to values at different HRTs, and it improved with a decrease in HRTs. Upon the decrease in HRT 6 h, an increase in the average current density was noted ( $95\text{--}232 \text{ mA m}^{-2}$ ), which was the highest value.

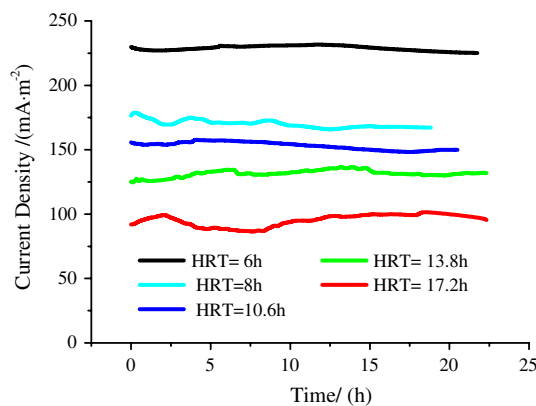
## Discussion

The effect of operating modes on substrate removal

In terms of the substrate removal, little difference was observed regarding the removal efficiencies of MFCs under different operating modes (Figs. 1, 3). Both of the MFCs showed a good capacity for simultaneous sulfide and nitrate removal regardless of their operating mode.



**Fig. 3** Substrate removal of the MFC in continuous operating mode



**Fig. 4** Electricity generation of the MFC in continuous operating mode

In the tested substrate concentration range, approximately 25.10–87.75 % influent sulfide was converted to sulfate, and about 95.61–99.85 % influent nitrate was transformed into nitrogen (Table 1). Under the tested HRT range, about 64.68–94.36 % influent sulfide was converted to sulfate, while nitrate conversion to nitrogen was 87.27–97.91 % (Table 1). It was inferred that nitrogen and sulfate were the main end products in both the operating modes.

**Table 1** Substrate removal of the MFCs in batch and continuous operating modes

Continuous operating mode					Batch operating mode				
HRT (h)	Conversion percentage (%)		Removal loading rate (kg (m <sup>3</sup> d) <sup>-1</sup> )		Influent sulfide concentration (mg S L <sup>-1</sup> )	Conversion percentage (%)		Removal loading rate (kg (m <sup>3</sup> d) <sup>-1</sup> )	
	Sulfate	Nitrogen	Sulfide	Nitrate		Sulfate	Nitrogen	Sulfide	Nitrate
17.2	89.60	97.89	0.42	0.08	60	25.10	97.88	0.04	0.01
13.8	94.36	97.91	0.52	0.09	300	87.75	99.85	0.20	0.03
10.6	79.19	97.07	0.68	0.12	540	68.66	98.44	0.36	0.06
8.0	68.19	93.72	0.87	0.15	780	78.68	96.67	0.52	0.09
6.0	62.48	87.27	1.18	0.20	1,020	64.68	95.61	0.68	0.12

In spite of non-obvious differences in the removal efficiencies and product conversion percentages of both MFCs, a substantial variation in the substrate removal rates was observed. For the respective influent sulfide and nitrate concentrations of 1,020 mg S L<sup>-1</sup> and 178.5 mg N L<sup>-1</sup>, their removal loading rates were 0.68 kg S (m<sup>3</sup> d)<sup>-1</sup> and 0.12 kg N (m<sup>3</sup> d)<sup>-1</sup>, respectively. In case of HRT at 6 h, the sulfide and nitrate removal loading rates were 1.18 kg S (m<sup>3</sup> d)<sup>-1</sup> and 0.20 kg N (m<sup>3</sup> d)<sup>-1</sup>, respectively (Table 1). Apparently, decreasing the HRT can bring a rapid increase in substrate removal compared to merely increasing the substrate concentration. The results were similar to those reported in the literature. In our previous study, the simultaneous anaerobic sulfide and nitrate removal process was operated in an upflow anaerobic sludge bed (UASB) reactor. Decreasing the HRT could better bring the substrate removal loading rate compared to increasing the substrate concentration [11].

Sulfide and nitrate can be toxic to microorganisms. Hence, the addition of the substrates in batch mode may have inhibitory effects on microorganisms leading to a decrease in removal efficiencies and loading rate. However, simultaneous anaerobic sulfide and nitrate removal in MFCs has a greater potential to elevate the process capacity when operated in continuous mode.

#### The effect of operating modes on electricity generation

In terms of electricity generation, a notable difference exists in the performance of MFCs in different operating modes (Figs. 2, 4).

In batch mode, the current density in the MFC always reaches its maximum value in the beginning, and then it rapidly decreases to a steady value, which is maintained for several hours (Fig. 2). During the whole period, the current densities varied greatly. A substantial difference exists between the maximum current densities and steady current densities, and the maximum value is 1.9–6.2 times higher than the steady value. Moreover, the maximum current

densities persist for a short period of time, and the steady current density is a better indicator to judge the performance of electricity generation in MFCs (Table 2).

When the MFC is operated in continuous mode, the current density remains stable during the operating period. The difference between the maximum current densities and steady current densities can be neglected, and the maximum value is 1.01–1.07 times greater than the steady value. To judge the electricity generation performance of both MFCs, the steady current density was used as the indicator. At respective influent sulfide and nitrate concentrations of 1,020 mg S L<sup>-1</sup> and 178.5 mg N L<sup>-1</sup>, the steady current density was 120 mA m<sup>-2</sup>. Applying HRT of 6 h, the steady current density was 229 mA m<sup>-2</sup> (Table 2). Apparently, decreasing HRT can elevate current density faster than increasing substrate concentration. The results agree with the reported literature. Rahimnejad et al. [19] studied the production of bioelectricity in MFC in batch and continuous systems. At an HRT of 6.7 h, the maximum current and power were 1,210 mA m<sup>-2</sup> and 283 mW m<sup>-2</sup>, respectively, which were higher than that in the batch system. Kim et al. [12] studied a continuous single-chamber MFC to treat wastewaters containing high nitrogen concentrations. After their adaptation to a high ammonia concentration, the power densities of continuous single-chamber MFCs were 1.1–3.3 times higher than those of batch MFCs.

The current investigation suggested that simultaneous anaerobic sulfide and nitrate removal in the microbial fuel cell has a greater potential for electricity generation in MFCs.

#### The effect of operating modes on electron utilization

MFCs are devices that use microorganisms as the catalysts to oxidize substrate and generate electric current. The microorganisms in the anodic chamber of the MFC produce protons and electrons by oxidizing the substrates. The produced electrons are transferred to the anode and flow to the cathode by an external circuit to produce the output current

**Table 2** Electricity generation of the MFCs in batch and continuous operating modes

Continuous operating mode				Batch operating mode					
HRT (h)	Maximum current density ( $\text{mA m}^{-2}$ )	Duration time (min)	Steady current density ( $\text{mA m}^{-2}$ )	Duration time (h)	Influent concentration ( $\text{mg S L}^{-1}$ )	Maximum current density ( $\text{mA m}^{-2}$ )	Duration time (min)	Steady current density ( $\text{mA m}^{-2}$ )	Duration time (h)
17.2	102	<10	95	>20	60	142	<10	23	Several
13.8	137	<10	131	>20	300	207	<10	50	Several
10.6	158	<10	153	>20	540	180	<10	78	Several
8	179	<10	170	>20	780	199	<10	103	Several
6	232	<10	229	>20	1,020	231	<10	120	Several

**Table 3** The transferred electrons and electronic quantity of the MFCs in different operating modes

Continuous operating mode				Batch operating mode					
HRT (h)	Released electrons (mmol)	Accepted electrons (mmol)	Electrons accepted by electrode (mmol)	Electronic quantity (C)	Influent concentration ( $\text{mg S L}^{-1}$ )	Released electrons (mmol)	Accepted electrons (mmol)	Electrons accepted by electrode (mmol)	Electronic quantity (C)
17.20	28.94	7.72	21.22	23.49	60.00	1.31	0.85	0.46	14.58
13.80	37.44	9.64	27.80	31.92	300.00	13.62	3.74	9.88	20.35
10.60	42.98	12.40	30.58	40.04	540.00	20.64	6.69	13.96	28.88
8.00	50.92	15.85	35.07	41.86	780.00	32.75	9.56	23.19	38.57
6.00	64.36	20.14	44.23	64.76	1,020.00	37.48	12.35	25.13	41.42

[7, 14]. The exploitation of the generated electrons in the form of electricity is a good indicator for judging MFCs in different operating modes.

During the simultaneous anaerobic sulfide and nitrate removal, nitrate was reduced, and sulfide was oxidized (Eq. 1). Although the electron acceptor and electron donor coexisted in the anode chamber, the electricity generation occurred in the MFC. The phenomenon can be explained on the basis of the difference between the electrons released on the anode and accepted on the cathode. The electrons transferred from simultaneous anaerobic sulfide and nitrate removal were calculated according to [4] and are shown in Table 3.

Regardless of the operating mode, the electron transfer increased with the increasing substrate concentration or decreasing HRT, and the electrons released by sulfide were always in excess compared to those accepted by nitrate. Moreover, the electrons transferred in the continuous operating mode of the MFC were greater than those in the batch operating mode. It seems that the number of transferred electrons is positively correlated with the output electricity. The electronic quantity was calculated to represent the actual electricity production, which was better than steady current density considering output electricity variation with time. Figure 5 shows the relation between electrons accepted on the electrode and electronic quantity in the MFCs, which better explains the process. It was inferred that output electricity in the MFC was linearly related with the accepted electrons on electrode ( $R^2 = 0.9656$  and  $R^2 = 0.9736$ ). The slope of the curve was the ratio of electricity generation and the number of electrons released, which represented the conversion efficiency of the released electrons as the electricity output. The larger the slope is, the higher the conversion efficiency. The slopes of the curves were 1.12 (batch mode) and 1.79 (continuous mode), respectively, which means that 1 mmol electrons

accepted by the electrodes were converted to 1.12 C of electricity in batch mode and 1.79 C in continuous mode.

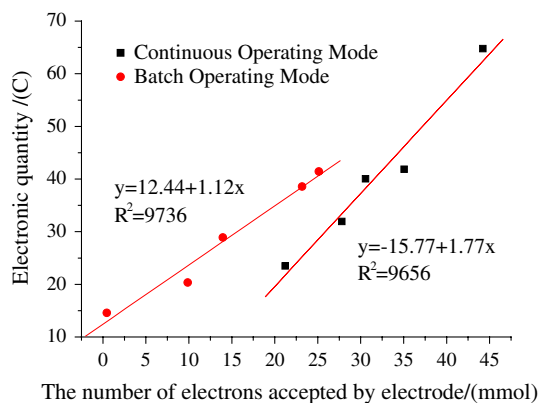
## Conclusion

Two operating modes (batch and continuous operating) were explored for the simultaneous sulfide and nitrate removal in two-chamber MFCs. In the tested range, the MFCs showed good removal efficiency with nitrogen and sulfate as the main end products regardless of the operating mode. The removal loading rate of MFCs in the continuous mode was much higher than that in the batch mode, and the current densities of the MFC in the continuous mode were more stable and higher than that in the batch mode. A linear relationship exists between the electrons released by substrates and accepted on the electrodes. The conversion efficiency of the released electrons to the electricity output in continuous mode was higher. The continuous operating mode is a suitable strategy for MFCs treating sulfide and nitrate simultaneously.

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## References

- Aelterman P, Rabaey K, Clauwaert P, Verstraete W (2006) Microbial fuel cells for wastewater treatment. *Water Sci Technol* 54(8):9–15. doi:10.2166/wst.2006.702
- APHA, Awwa, WPCF (1998) Standard methods for the examination of water and wastewater, 20th edn. American Public Health Association, Washington, DC
- Cai J, Zheng P (2013) Simultaneous anaerobic sulfide and nitrate removal in microbial fuel cell. *Bioresour Technol* 128:760–764. doi:10.1016/j.biortech.2012.08.046
- Cai J, Zheng P, Zhang J, Xie Z, Li W, Sun P (2013) Simultaneous anaerobic sulfide and nitrate removal coupled with electricity generation in Microbial Fuel Cell. *Bioresour Technol* 129:224–228. doi:10.1016/j.biortech.2012.11.008
- Chung K, Okabe S (2009) Continuous power generation and microbial community structure of the anode biofilms in a three-stage microbial fuel cell system. *Appl Microbiol Biotechnol* 83(5):965–977. doi:10.1007/s00253-009-1990-z
- Cirne DG, van der Zee FP, Fernandez-Polanco M, Fernandez-Polanco F (2008) Control of sulphide during anaerobic treatment of S-containing wastewaters by adding limited amounts of oxygen or nitrate. *Rev Environ Sci Bio/Technol* 7(2):93–105. doi:10.1007/s11157-008-9128-9
- Du Z, Li H, Gu T (2007) A state of the art review on microbial fuel cells: a promising technology for wastewater treatment and bioenergy. *Biotechnol Adv* 25(5):464–482. doi:10.1016/j.biotechadv.2007.05.004
- Garcia-de-Lomas J, Corzo A, Portillo MC, Gonzalez JM, Andrades JA, Saiz-Jimenez C, Garcia-Robledo E (2007) Nitrate stimulation of indigenous nitrate-reducing, sulfide-oxidising



**Fig. 5** The relation between electrons accepted by the electrode and electronic quantity in the MFCs

- bacterial community in wastewater anaerobic biofilms. *Water Res* 41(14):3121–3131. doi:10.1016/j.watres.2007.04.004
9. Habermann W, Pommer EH (1991) Biological fuel cells with sulphide storage capacity. *Appl Microbiol Biotechnol* 35(1):128–133
  10. Jin R, Yang GF, Zhang QQ, Ma C, Yu JJ, Xing BS (2013) The effect of sulfide inhibition on the ANAMMOX process. *Water Res* 47(3):1459–1469. doi:10.1016/j.watres.2012.12.018
  11. Jing C, Ping Z, Mahmood Q (2010) Influence of various nitrogenous electron acceptors on the anaerobic sulfide oxidation. *Bioresour Technol* 101(9):2931–2937. doi:10.1016/j.biortech.2009.11.047
  12. Kim H-W, Nam J-Y, Shin H-S (2011) Ammonia inhibition and microbial adaptation in continuous single-chamber microbial fuel cells. *J Power Sources* 196(15):6210–6213. doi:10.1016/j.jpowsour.2011.03.061
  13. Lee C, Ho K, Lee D, Su A, Chang J (2012) Electricity harvest from nitrate/sulfide-containing wastewaters using microbial fuel cell with autotrophic denitrifier, *Pseudomonas* sp C27. *Int J Hydrogen Energ* 37(20):15827–15832. doi:10.1016/j.ijhydene.2012.01.092
  14. Logan BE, Hamelers B, Rozendal RA, Schrorder U, Keller J, Freguia S, Aelterman P, Verstraete W, Rabaey K (2006) Microbial fuel cells: methodology and technology. *Environ Sci Technol* 40(17):5181–5192. doi:10.1021/es0605016
  15. Mahmood Q, Zheng P, Cai J, Hayat Y, Hassan MF, Wu DL, Hu BL (2007) Sources of sulfide in waste streams and current biotechnologies for its removal. *J Zhejiang Univ Sci A* 8(7):1126–1140. doi:10.1631/jzus.2007.A1126
  16. Mahmood Q, Zheng P, Cai J, Wu D, Hu B, Li J (2007) Anoxic sulfide biooxidation using nitrite as electron acceptor. *J Hazard Mater* 147(1–2):249–256. doi:10.1016/j.jhazmat.2007.01.002
  17. Oliveira VB, Simões M, Melo LF, Pinto AMFR (2013) Overview on the developments of microbial fuel cells. *Biochem Eng J* 73:53–64. doi:10.1016/j.bej.2013.01.012
  18. Pant D, Van Bogaert G, Diels L, Vanbroekhoven K (2010) A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production. *Bioresour Technol* 101(6):1533–1543. doi:10.1016/j.biortech.2009.10.017
  19. Rahimnejad M, Ghoreyshi AA, Najafpour G, Jafary T (2011) Power generation from organic substrate in batch and continuous flow microbial fuel cell operations. *Appl Energy* 88(11):3999–4004. doi:10.1016/j.apenergy.2011.04.017
  20. Zhang L, De Schryver P, De Gussem B, De Muyenck W, Boon N, Verstraete W (2008) Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: a review. *Water Res* 42(1–2):1–12. doi:10.1016/j.watres.2007.07.013