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Energy-Efficient Treatment of Organic Wastewater Streams using a Rotatable Bioelectrochemical Contactor (RBEC)

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Abstract

A membraneless bioelectrochemical system - Rotatable Bio-Electrochemical Contactor (RBEC) consists of an array of rotatable electrode disks was developed to convert the chemical energy from wastewater organics (acetate) directly into electricity. Each rotatable electrode disk had an upper-air exposing and a lower-water submerging halves. Intermittent rotation (180°) enabled each halve to alternately serve as anode and cathode. Removal of chemical oxygen demand (COD) was increased by 15% (from 0.79 to 0.91 kg COD·m⁻³·d⁻¹) by allowing electron flow from the lower to the upper disk halves. Coupling with a potentiostat could alleviate cathodic limitation and increased COD removal to 1.32 kg COD·m⁻³·d⁻¹ (HRT 5 h). About 40% of the COD removed was via current, indicating that the biofilm could use the lower half disk as electron acceptor. The RBEC removed COD more energy-efficiently than conventional activated sludge processes as active aeration is not required (0.47 vs. 0.7-2.0 kWh kgCOD⁻¹).

**Keywords:** Bioelectrochemical systems, Microbial fuel cells, Biofilms, Waste to energy, Clean technology
1. Introduction

Recently, bioelectrochemical systems (BES) such as microbial fuel cells (MFC) and microbial electrolysis cells (MEC) have emerged as a new environmental technology for recovering valuables such as energy from organic waste streams (Rabaey et al. 2007; Rozendal et al. 2008). These systems involve microorganisms to convert the chemical energy of the organic pollutants in wastewater directly into electricity or other energetic products such as hydrogen gas (Logan et al. 2008; Rozendal et al. 2008). However, up-scaling BES to an industrial scale still remains as a challenge. To generate electron flow, a BES should have several generic features. Firstly, an electron donor (e.g. organics present in a wastewater) is oxidized by an electrochemically active biofilm which can subsequently transfer the liberated electrons to an electrode (here anode). Secondly, the electrons at the anode are driven by a potential gradient to flow toward a cathode via an external electrical circuit. Electrical energy is generated if a suitable resistive load is located between the two electrodes. Thirdly, the electrons at the cathode react with a soluble electron accepting species (e.g. oxygen, nitrate) which becomes reduced. Similar to a hydrogen fuel cell (e.g. proton exchange membrane fuel cell), electricity generation in a BES is sustained only when the ionic charges between the anode and cathode is balanced. For each electron flowing across the external circuit, a positively /negatively charged ionic species must be transferred from the anode / cathode. The buildup of a proton gradient(pH splitting) is recognized as the key obstacle for efficient current generation in MFC (Harnisch and Schroder 2009; Rozendal et al. 2006). Such pH splitting phenomena could lead to as high as a 6 pH units difference between the two electrodes (Clauwaert et al. 2008), hence severely stifling the driving force of the system (i.e. potential difference between anode and cathode) as each unit of pH gradient represents an overpotential (potential loss) of 59 mV (Nernst equation). Correcting the pH by acid/ base dosing or addition of a concentrated buffer (e.g. phosphate buffer) is not feasible for large-
scale application, although these methods are effective in laboratory trials (Cheng et al. 2010).

A loop-concept has been described as a mitigation strategy for the aforementioned pH limitation during MFC operation, where the acidified anodic effluent of a MFC served as the influent for the cathode in a two-compartment configuration (Freguia et al. 2007). However, the obligatory requirement of mechanical recirculation of wastewater throughout the system against gravity may limit process scale-up (Clauwaert et al. 2009; Freguia et al. 2007).

Here, a new BES configuration, rotatable bioelectrochemical contactor (RBEC) is described and evaluated for its capacity to convert soluble organics directly into electrical current without using conventional pH control methods or the need of energy consuming wastewater re-circulation. While similar to the well-known rotating biological contactor (RBC), the RBEC has several distinctive features: (i) It consists of an array of electrically conductive disks mounted onto a horizontal rotating shaft, facilitates the growth of electroactive biofilm; (ii) Each electrode disk consists of a water-submerged and a headspace-exposed half disk, which is partially immersed in the waste stream; (iii) The air-water interface served as a “virtual membrane” separating the two redox zones (half disks) eliminating the need of an ion-exchange membrane. This work aims at quantifying the performance of the RBEC as a MFC for electricity generation. The effect of external power input on the organic treatment performance of the RBEC is also described. Energy consumption and treatment performances are compared with the conventional activated sludge processes.

2. Materials and Methods

2.1 Construction of the RBEC Reactor
The RBEC reactor consists of three major components: (1) a reactor vessel; (2) a rotatable electrode disk assembly; and (3) a computer controllable stepper motor unit (Figure 1). The reactor vessel consists of a cylindrical Perspex transparent water pipe (298 mm length; 140 mm diameter) with its two ends covered by two separate square Perspex side plates (160 x 160 mm). A rubber O-ring was placed between each side plate and the centre pipe to assure air and water tightness. A rotatable electrode disk assembly consists of a Perspex horizontal central rotatable shaft. Two separate stainless steel current collecting strips were independently mounted onto the upper and lower sides of the shaft. 20 sets of electric conductive disks were mounted onto a central horizontal rotatable shaft. A computer controllable stepper motor unit consists of a stepper motor, a stepper motor driver, and an analog output card (Labjack U12). The motor was tightly mounted onto the side plate of the reactor vessel. A gear disk (one-to-seven reduction) was used to convey the mechanical action of the motor to the central rotatable shaft.

2.1.1 Design of Two Half Disks Serving as Anode and Cathode

Each electrode disk consists of two halves; an upper air-exposed and a lower water submerged half. Each half consists of a stainless steel current collecting mesh. Electrically conductive carbon fiber sheet was mounted onto both sides of the mesh. The upper and the lower halves were physically and hence electrically separated from each other. Each half has a small extension of the stainless steel mesh which serves as the electric contact with a stainless steel current collector located at the central shaft. Electrical connection between the stainless steel current collecting strips and the external circuit was completed with two individual copper electrical wires. A Perspex plastic o-ring was used to connect each pair of
electrode disks with the central shaft and to maintain a constant distance with the neighboring disks. The estimated total projected surface area (water submerged) of the 20 disk halves was 947 cm$^2$. This value is used for calculating the current and power densities. After filling up the RBEC reactor with the wastewater, about 5 mm of the bottom edge of the air-exposed half disks were immersed in the water to enable ionic balance without the use of an ion exchange membrane.

2.2 Process Monitoring and Control

In general, a computer program LabVIEW™ (version 7.1 National Instruments™) was developed to continuously control and monitor the RBEC process. Voltage signals were recorded at fixed time intervals via the LabVIEW program interfaced with a high precision voltage data acquisition board (DAQ) (National Instruments™ NI4350). All electrode potential (mV) described in this study refers to values against Ag/AgCl reference electrode (ca. +197 mV vs. standard hydrogen electrode). When the RBEC was operated as a MFC, the potential differences between the air-exposed cathode and water submerged anode (i.e. cell voltage); and between the submerged disks and a silver-silver chloride reference electrode (Bioanalytical System, RE5) were continuously monitored by the DAQ. When a potentiostat was used to supply extra electrical power to the system and to maintain a constant potential of the water submerged anode, the current was directly recorded from the potentiostat.

Rotation of the electrode disks was fully automated. The stepper motor and its driver is calibrated such that upon receiving a proper signal from the computer program (via a Labjack™ analog output card), the electrode disks could be rotated at a defined time interval either for a full-(360°) or a half-(180°) rotation (intermittent-flipping). In the latter case, each
half disk could intermittently serve as a submerged anode and an air-exposed cathode (Figure S1 in supplementary material file). When the RBEC was coupled to a potentiostat, a computer controllable relay-switch was fabricated to intermittently switch over the connection between the working electrode of the potentiostat and the two half disks. The air-exposed halves always serve as the counter electrode. Hence, both half disks would alternately expose to an identical anodic and cathodic environment during the intermittent-flipping operation.

2.3 Bacterial Inoculum and Synthetic Wastewater

A return activated sludge collected from a local municipal wastewater treatment plant was used as the inoculum. It was stored at 4°C prior use. A synthetic wastewater was used throughout the study. Unless stated otherwise, it consisted of (mg L\(^{-1}\)): NH\(_4\)Cl 125, NaHCO\(_3\) 125, MgSO\(_4\)·7H\(_2\)O 51, CaCl\(_2\)·2H\(_2\)O 300, FeSO\(_4\)·7H\(_2\)O 6.25, and 1.25 mL L\(^{-1}\) of trace element solution, which contained (g L\(^{-1}\)): ethylene-diamine tetra-acetic acid (EDTA) 15, ZnSO\(_4\)·7H\(_2\)O 0.43, CoCl\(_2\)·6H\(_2\)O 0.24, MnCl\(_2\)·4H\(_2\)O 0.99, CuSO\(_4\)·5H\(_2\)O 0.25, NaMoO\(_4\)·2H\(_2\)O 0.22, NiCl\(_2\)·6H\(_2\)O 0.19, NaSeO\(_4\)·10H\(_2\)O 0.21, H\(_3\)BO\(_4\) 0.014, and NaWO\(_4\)·2H\(_2\)O 0.050. Sodium acetate (5 to 10 mM) was used as the sole electron donor throughout the study. Yeast extract (0.1-1 g L\(^{-1}\) final concentration) was added as bacterial growth supplement. Unless otherwise stated, the initial pH of the synthetic wastewater was adjusted to 6.9-7.2 using either 1M HCl or 4M NaOH. No additional pH buffer was added.

2.4 Reactor Operation
2.4.1 Start-up as a Microbial Fuel Cell

The RBEC was loaded with a synthetic wastewater amended with an activated sludge (ca. 2 g MLSS L\(^{-1}\)). The total liquid volume in the reactor was 1.75 L. Initially the reactor was operated in a batch mode as a MFC for about two months (Figure 1A). A variable external resistor (2 to 1 M\(\Omega\)) was used to connect the upper and the lower disk half, completing the external electrical circuit of the system. Unless otherwise stated, the RBEC was operated at ambient temperature (22 -25\(^o\)C) and atmospheric pressure. Polarization curve analysis was regularly performed to evaluate MFC performance over time (Logan et al. 2006). Briefly, this analysis was done by decreasing the external resistance from 1 M to 5 \(\Omega\) in a stepwise manner. For each external resistance setting, at least 5 min waiting period was given to obtain steady state values of current (I) and voltage (V). These values were used to obtain the corresponding power output (P) according to an equation of \(P = V \times I\). Power and current densities were obtained by normalizing the P and I with the projected surface area of the submerged half disks (i.e. 947 cm\(^2\)), respectively. Correlation between the submerged anode potential and the current density was further obtained from the data of the polarization curve analysis. This correlation is useful to evaluate anodophilic property of the electrochemically active biofilm in a MFC (Cheng et al. 2008). Acetate concentration of the wastewater was quantified regularly to obtain COD removal rate at different experimental runs (Cheng et al. 2008). Chemical oxygen demand (COD) was derived from acetate concentration assuming 1.067 g COD·g acetate\(^{-1}\). After start up, COD removal rates at external resistances of 2 \(\Omega\) and open circuit were compared to test the effect of current on COD removal. The effect of disk rotation (full-turn, half-turn or no rotation) on COD removal was assessed at open circuit.
2.4.2 Coupling the RBEC with a Power Source

After a two months operation as a MFC, the RBEC was coupled with an electrical power source (here a potentiostat) to overcome any cathodic limitation in the system. The working (WE), counter (CE) and reference electrodes (RE) of the potentiostat (Model no.362, EG&G, Princeton Applied Research, Instruments Pty. Ltd.) were connected to the submerged anode, air-exposed cathode and the reference electrode, respectively (Figure 1B). Unless specified otherwise, the anode potential was maintained at -300 mV.

The potentiostat-assisted RBEC was initially operated in fed-batch mode for approximately one week before switching into continuous mode. A synthetic wastewater supplemented with 10 mM acetate was continuously fed to the reactor at a flow rate between 2.5 and 6 ml min$^{-1}$, which corresponded to a hydraulic retention time (HRT) between 4.9 and 11.7 h; and an organic loading rate (OLR) between 1.3 and 3.1 kg COD·m$^{-3}$·d$^{-1}$. COD removal rate was obtained according to: \( \frac{\text{COD}_{\text{In}} - \text{COD}_{\text{Out}}}{\text{HRT}} \), where \( \text{COD}_{\text{In}} \) and \( \text{COD}_{\text{Out}} \) are COD concentrations (mg·L$^{-1}$) of the influent and effluent, respectively. Both the influent reservoir and the effluent were kept at 4°C to avoid microbial deterioration.

3. Results and Discussion

3.1 Operation as a Microbial Fuel Cell for Electricity Generation

The described reactor was constructed and operated as a fed-batch MFC reactor for about two months. To generate electricity, the submerged anodic half disk of the RBEC must first be polarized (biologically) at a potential low enough to enable spontaneous electron flow to the air-cathode. Under open circuit condition, the microbial inoculum (here activated sludge) could reduce the potential of the anodic half disks to a steady level of -453 mV within
16 hours (data not shown). Thereafter, the reactor was operated by rotating the electrode
disks full turns every 15 min. This allowed the bacteria to establish as an electrochemically
active biofilm on both the submersed anodic- and the air exposed cathodic-half disks over
time. The performance of the RBEC was periodically recorded over 50 days by using
polarization and power curve method (Figure S2 in supplementary material file). The current
and power outputs of the RBEC reactor increased over time reaching a maximum current
density and power density of 0.075 A·m$^{-2}$ and 8.4 mW·m$^{-2}$, respectively. This gradual
increase in electrical output was attributed to microbial enhancement of either the cathodic or
anodic half-reaction.

To determine which of the two half-reactions was stimulated by the developing
biofilm, a series of current/potential curves was plotted (Figure S3 in supplementary material
file). A clear increase in the anodic reaction could be observed from the fact that the bacteria
could generate more current at any selected anodic potential. For instance, at an anodic
potential of -500 mV the bacteria could generate twice as much current on day 50 compared
to day 38 (Figure S3). No clear trend was observed for the change in cathodic potential over
time (data not shown), suggesting that the biofilm has become more capable of using the
water-immersed anode as their electron acceptor.

3.1.1 Transfer of Oxidizing Power via Current instead of Mass Transfer of $O_2$

Although the design of the RBEC is similar to a traditional rotating biological
contactor (RBC), their underlying principles of COD removal are different. In RBC the
oxidizing power required for the microbial oxidation of organics is provided by turning the
contactor disks which facilitates mass transfer of oxygen to the previously submersed biofilm.
Contrarily, the RBEC is based on electron transfer instead of mass transfer: The oxidizing power from the oxygen exposed headspace half disk (cathode) is provided to the submersed biofilm by electron flow which does not require rotation of the disk.

To quantify the COD removal via electron transfer from the submersed to the air-exposed half disk, the effect of allowing electron flow (with a 2 Ω external resistor) on COD removal rates was recorded (Figure 2). A COD removal rate of about 0.17 kg COD·m\(^{-3}\)·d\(^{-1}\) (from 0.48 to 0.65 kg COD·m\(^{-3}\)·d\(^{-1}\)) was attributed to electron flow, while a COD removal rate of 0.16 kg COD·m\(^{-3}\)·d\(^{-1}\) (from 0.32 to 0.48 kg COD·m\(^{-3}\)·d\(^{-1}\)) was due to enhanced mass transfer by rotation (disks were rotated one turn every 15 min at one rpm to approach RBC operation) (Figure 2C).

It is noteworthy that in the above experiment a significant level of COD was degraded (0.32 kg COD·m\(^{-3}\)·d\(^{-1}\)) even in the absence of any deliberate supply of oxidizing power (neither rotation nor allowing electron flow in the external circuit). This background COD removal is more than what would be expected from oxygen diffusion to the submersed biofilm. An unaccountable flow of oxidizing power via a short-circuit of the submersed part of the air exposed half disk may explain some of the COD loss. The observation of current flow that is not measured as it by-passes the external circuit has been recently detected to interfere with MFC and termed as “parasitic current” effect (Harnisch and Schroder 2009) (See Figures S4-6 in supplementary material file for further discussion).

### 3.1.2 Sequential Flipping the Electrode Disks allows Alternate Current Generation

It has been shown that a BES biofilm could catalyze both anodic substrate oxidation and cathodic oxygen reduction in a two-chamber BES, causing an intermittent polarity.
reversal of the system (Cheng et al. 2010). Such bidirectional microbial electron transfer could alleviate both the pH gradient and cathodic oxygen reduction limitations in the BES. The same concept was tested here with the RBEC. The disks were intermittently rotated by 180° (“flipped” every 1h) such that each half disk was alternately exposed to the wastewater and the air (Figure S1). The RBEC was operated with this flipping action for 1 week.

The result showed that the intermittent-flipping action could reverse the polarity of current (ranged from -6.7 to +7.5 mA) (Figure 3A). When current was interrupted (open circuit), the intermittent-flipping resulted in a 2.5-fold increase in COD removal rate compared to the control without rotation (from 0.32 to 0.79 kg COD·m⁻³·d⁻¹) (Figure 6B). Since the biofilm was alternately exposed to the wastewater and air, under anaerobic condition (i.e. when the half-disks were submerged in the wastewater) the biofilm may store the excess amount of substrate available (here acetate) from the wastewater as intracellular polymers such as polyhydroxybutyrate (PHB) (Van Aalst-van Leeuwen et al. 1997; Van Loosdrecht et al. 1997). Upon the subsequent half-rotation of the disks, the bacteria can oxidize their storage materials using oxygen as electron acceptor. Hence, in addition to the parasitic current effect, bacterial storage may account for the enhanced COD removal under the intermittent-flipping operation mode. Overall, COD removal in the RBEC appeared to be a combination of bioelectrochemical/ purely biological events.

3.2 Additional Voltage facilitated Microbial-Driven Current Generation and COD Removal

Similar to most other air-cathode based MFC, the sluggish cathodic oxygen reduction has also limited the electrical output of the RBEC (Clauwaert et al. 2009; Kim et al. 2007;
Venkata Mohan and Srikanth 2011; Wang and Han 2008) (Clauwaert et al. 2009; Kim et al. 2007; Wang and Han 2008). Without a good cathodic reaction, the anode became an unfavorable electron acceptor for the biofilm. In the literature, cathodic limitation can be overcome by providing extra voltage into the BES. A well known example is cathodic hydrogen production using MEC (Logan et al. 2008). In the present study, a potentiostat was used to overcome the cathodic overpotential and to maintain a suitable anode potential of -300 mV for the biofilm to anodically oxidize the substrate. The cathodic half-disks were remained aerobic.

In the absence of acetate in the medium, a low background current of ~ 2 mA and a cathodic potential of -300 mV were obtained (Figure 4A, B). Addition of acetate could immediately increase the current as observed in the previous, non-potentiostatic runs but the current was about 10-fold higher (about 60 mA) (Figure 4A). Further, a coulombic recovery of 40% was obtained under this potentiostatic operation as opposed to only 5% as noted in previous non-potentiostatic mode. After operating for several batch cycles (ca. 1 week), the RBEC was switched into a continuous mode to avoid substrate limitation. This enabled a sustainable current production between 40 and 60 mA with an average COD removal rate of 1.15 ± 0.05 kg COD·m⁻³·d⁻¹ (Figure 4C).

3.2.2 Sequential Half Rotation Inversed Polarity of the System and alleviated the Continuous Cathode Alkalization

To establish a suitable biofilm capable of catalyzing both anodic acetate oxidation and cathodic oxygen reduction on both half disks (i.e. reversal of polarity), the potentiostatic process was modified such that the disk was only rotated for half a turn (180°) instead of a
full turn (360°) (Figure 5). Each half disk could serve as a submerged anode and an air-
exposed cathode intermittently. After a few days operation, the original “air-exposed half
disk” (cathode) gradually became more capable of catalyzing the anodic acetate oxidation,
resulted in an overall accelerated COD removal. At 51, 61 and 92 h, the COD oxidation rates
were 0.60, 0.88 and 1.31 kg COD·m⁻³·d⁻¹, respectively (Figure 5A).

The cathodic oxygen reduction consumes protons according to equation: O₂ + 4e⁻ + 4H⁺ → 2H₂O. The localized pH at the cathode disk was expected to increase over time.

According to Nernst equation, a 10 fold increase of hydroxide ion (i.e. ΔpH = +1) causes a
reduction of cathodic potential by 59 mV (Bard and Faulkner 2001). This represents a loss of
electromotive force and thereby additional energy is required to compensate for this loss in
order to sustain the forward cathodic reaction. Neutralizing the cathode alkalinity by polarity
inversion may alleviate this additional energy demand (Cheng et al. 2010). Here, the effect of
intermittent flipping of the electrode discs on the cathode pH was evaluated (Figure 6).

Before a flipping event (from 5 to 65 min), the cathode pH (disc 1) increased from 7.0 to 9.0
and the cathode potential became more negative (-74 mV/pH). Similar trend of cathodic
alkalization was observed for the opposing half disks (from 65 to 125 min). After another
flipping event (at 125 min), the half disks that were original alkalized had became neutralized.
The continuous build-up of alkalinity at the air-cathode could thus be avoided.

3.3 Energy Evaluation and Implications of the Electrochemically Assisted RBEC process

It may seem defeating the purpose of treating wastewater in a microbial fuel cell that
requires additional energy input to overcome the cathodic overpotential. However, the actual
ergy requirement of the potentiostatic RBEC process appears to be comparable with
conventional activated sludge (AS) processes (Table 1). The COD removal rate achieved by the RBEC fall within the range of the AS processes, suggesting that the COD removal of the RBEC process is comparable to that of the AS process. However, the RBEC process required less energy input per COD removed (0.47 kWh kg COD$^{-1}$) than the AS processes (0.7-2.0 kWh kg COD$^{-1}$) or per volume of water treated (88 vs. 430 kWh ML$^{-1}$). These figures indicate that substantial energy saving may be achieved using the RBEC for the treatment of wastewater organics.

Overall, the working principle of the RBEC is demonstrated. However, further process optimization is required. These efforts may include: (i) optimizing current density and COD removal by increasing the electrode surface area (e.g. number of contactor disks) per liquid volume ratio; (ii) minimizing overpotential of the cathodic oxygen reduction by modifying the electrode with a suitable catalyst or using more effective electrode materials; (iii) production of valuable products or energy carriers from organic waste streams.

4. Conclusions

(i) The RBEC can operate as a MFC, achieving net electricity recovery from wastewater organics.

(ii) Removal of wastewater organics was achieved without (a) adjusting the pH of the wastewater; (b) aeration of the wastewater or catholyte as the cathode is exposed to air; (c) ion exchange membrane nor wastewater recirculation.

(iii) Intermittent disk flipping and polarity inversion established electroactive biofilms at both half disks. The biofilms could survive under both anodic and cathodic conditions.
The electrochemically assisted RBEC process could remove COD more energy efficient than the conventional activated sludge process.

5. Acknowledgements
The work described in this paper was funded by a Murdoch University Discoverers Grant. We thank Mr. Fritz Wagen (mechanical workshop, Murdoch University) for his contribution in the design and manufacture of the RBEC reactor, and Mr. John Snowball (electronic workshop, Murdoch University) for his technical assistance with the electronic settings in this study.

6. References


6. **Appendix A** – Supplementary materials
Figure Captions

Figure 1. A schematic diagram of the RBEC system: (A) operated as a microbial fuel cell for electricity generation (batch operation); (B) coupled with a potentiostat for enhanced cathodic oxygen reduction operated at a continuous mode. (1) computer monitoring and control; (2) the RBEC reactor unit; (3) reference electrode; (4) variable external resistor; (5) central rotating shaft; (6) electrode disc assembly; (7) computer controllable stepper motor; (8) a computer controllable relay switch interfacing the half-discs and the potentiostat; (9) peristaltic pump; (10) heat exchanger to warm up the cold feed; (11) influent feed reservoir, at ~4°C ice bath; (12) effluent holding tank, at ~4°C ice bath. Note: figure not drawn to scale; RE: reference electrode; CE: counter electrode (i.e. cathode); WE: working electrode (i.e. anode).

Figure 2. Changes in (A) current, (B) anodic potential and (C) acetate concentration in the RBEC reactor operated at closed or open circuit.

Figure 3. Effect of regular half-rotation of electrode dices on (A) current, anodic potential and (B) acetate concentration in the RBEC reactor operated at close (2 ohm) and open circuit. The discs were flipped (180°) every 1 hour. Solid arrows in A indicate flipping events (~1 min). Switching from positive to negative current (or vice versa) indicate the polarity of the system was inverted.

Figure 4. Performance of a potentiostat-controlled RBEC operated at (A, B) batch mode and (C, D) continuous mode. The submerged anode discs were poised at -300 mV vs. Ag/AgCl. The discs were rotated (360°) once per 15 min.
Figure 5. Intermittent Disk-flipping operation of the RBEC with the submerged anodic disks controlled at a potential of -400 mV. (A) Anodic current over time; (B) electrode disk potential over time; Solid arrow: disk 1 as the anode; dotted arrow: disk 2 as the anode. Prior to the experiment, the biofilm at disk 2 was more anodophilic than that at disk 1. In the first 16 h the disks were flipped once every 30 min, thereafter once per hour.

Figure 6. Effect of intermittent flipping of the electrode on the pH of the air-exposed cathode.
Table 1 Treatment performance and energy requirement of the RBEC process and conventional activated sludge (AS) processes.

<table>
<thead>
<tr>
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<th>Conventional AS Processes</th>
<th>RBEC Process&lt;sup&gt;a&lt;/sup&gt;</th>
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<tr>
<td>#COD removal rate (kg COD m&lt;sup&gt;-3&lt;/sup&gt; day&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.5 - 2&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>Energy input per COD removed (kWh kg COD&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>0.7 - 2&lt;sup&gt;c&lt;/sup&gt;</td>
<td>¥0.47</td>
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<tr>
<td>Energy per volume of wastewater treated (kWh ML&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>430 - 940&lt;sup&gt;d&lt;/sup&gt;</td>
<td>¥88</td>
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<sup>a</sup> Values for the RBEC process are calculated based on data obtained in Figure 10 (91-100 h).

<sup>b</sup> Adapted from (Logan et al. 2006)

<sup>c</sup> Adapted from (Tchobanoglous et al. 2003)

<sup>d</sup> Adapted from (Keighery 2004).

<sup>#</sup> COD content of acetate was estimated assuming 1.067 g COD per 1.0 g acetate.

<sup>¥</sup> The values include the energy consumption by the stepper motor (0.083 Wh per one rotation).
List of Figures

Figure 1
Figure 2

(A) Current (mA) vs. Time (h)

(B) Anodic Potential (mV vs. Ag/AgCl) vs. Time (h)

(C) Acetate Concentration (mM) vs. Time (h)

- 2 Ohm (Rotated 360° Every 15 min)
- Open Circuit (Rotated 360° Every 15 min)
- Open Circuit (No Rotation)
Half-Turn (180°) Disc Rotation Every 1h:

(A)

(B)

0.52 mM·h⁻¹  Open Circuit
\( (R^2 = 0.99) \)

0.60 mM·h⁻¹  2 Ohm
\( (R^2 = 0.95) \)
Figure 4

(A) Current (mA) vs. Time (h) for Acetate Starved (Batch mode) and Acetate Saturated (Continuous mode) experiments.

(B) Potential (mV vs. Ag/AgCl) vs. Time (h) for the same experiments.

(C) Comparison of COD removal rates: 1.19 kg COD·m⁻³·d⁻¹ for Acetate Saturated and 1.16 kg COD·m⁻³·d⁻¹ for Acetate Starved.

(D) Acetate concentration (mM) vs. Time (h) for the experiments.
Figure 5

(A) | (B)
---|---

Current (mA) vs. Time (h)

Potential (mV vs. Ag/AgCl) vs. Time (h)

Fixed Anodic Potential

Intermittent Flipping

Cathodic Potential
Figure 6

(A) Cathode: Disk 1, Rotated 180°, Cathode: Disk 2

(B) Submerged Discs (Anode) vs. Air-Exposed Discs (Cathode)

-74 mV/pH, -86 mV/pH
Highlights

- Rotatable bioelectrochemical contactor (RBEC) as a new BES configuration
- Rotatable disk divided into a lower anodic and upper cathodic halves
- Intermittent disk flipping established biofilms at both disk halves and allowed polarity inversion
- Alternating anodic and cathodic catalysis alleviated the typical pH imbalance limitation
- RBEC as MFC yielded net electricity but input of extra power further increased current and COD removal