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Effects of irrigation and water content of packing materials on a thermophilic biofilter for SO₂ removal: Performance, oxygen distribution and microbial population

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ABSTRACT

The water content (WCR) of packing materials is a key factor that determines the success of biofilters, particularly thermophilic bioreactors, for off-gas treatment. An optimum WCR can be accomplished by directly irrigating packing materials. In this study, the performance of a thermophilic biofilter for SO₂ removal was investigated by different irrigation times. The removal efficiency of SO₂ was largely influenced by the water content of packing materials, which varied with irrigation time. An average SO₂ removal efficiency of 98% could be achieved when WCR was >80%. The thermophilic biofilter required daily irrigation to maintain the optimum WCR. Oxygen distribution varied in polyurethane foam cubes (PUFCs) at different WCRs. PUFCs with a high WCR provided aerobic-low oxygen-aerobic areas. Microbial population also varied accordingly. For the thermophilic biofilter in treating SO₂, over 80% was the optimal WCR which could be achieved by continuous irrigation.

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1. Introduction

Biotechnologies, including biofilters, bioscrubbers, and biotrickling filters, have been widely applied to treat off-gas because of their high efficiency, cost effectiveness, convenient operation, and small footprint [1–3]. Bench- scale and pilot-scale studies have shown that exhaust streams containing various pollutants such as sulfur dioxide [4,5], ammonia [6] and volatile organic compounds (VOCs) [7], can be successfully treated with bioreactors. A biotrickling filter followed by a biological post-treatment unit has been developed to eliminate SO₂ from flue gases. Nearly 100% of SO₂ can be effectively removed by this kind of combined bioreactor [4]. Emissions generated from industrial processes, especially fossil fuel combustion and petroleum refinery, contain sulfur compounds and VOCs at temperatures higher than 50 °C [8]. Alternatively, the application of thermophilic biofilters that utilizes the metabolic activity of thermophilic organisms for the treatment of off-gas at high

temperature would increase elimination rates and the desired efficiency is achieved at shorter reaction times [9,10].

In general, packing materials are packed in gaseous bioreactors for mass transfer and microbial attachment [11]. The water content of packing materials is a key factor that determines the success of biofilters and thus must be controlled to avoid the excessive wetting or drying of filter beds [12]. Inadequate management of water content may cause malfunctions in biofilters [13]. For instance, a severe decrease in average water content from 70% to 30% results in a loss of approximately 50% in biofilter performance [14]. A peat biofilter with various initial water contents has been used to treat ethanol vapor, but its elimination capacity sharply decreases from 27 g ethanol/m³/h to 4 g ethanol/m³/h when the water content of packing materials is reduced from 70% to 60% [15]. The performance of biofilters is also dependent on microbial activity during waste gas treatment processes [16]. Microorganisms need minimum water content for optimal growth and activity. Some species, such as *Bacillus* sp., most microorganisms cannot survive in packing materials with very low water content [17].

In bioreactors, gas streams flow through a water-insoluble solid support, which contains an aqueous static phase conducive for soluble substrate dissolution and microbial growth [18]. Hence, biofilters may be regarded as three-phase systems comprising a gaseous phase, an aqueous phase (nutrient solution), and a solid phase (packing material and biofilm). In this heterogeneous

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medium, the transfer of pollutants from a gaseous phase to an aqueous phase is a fundamental step in abatement [19]. However, excess water reduces the porosity of packing material and thus limits mass transfer and creates anaerobic zones [20]. Zhu et al. (1998) found that the mass transfer resistance in the liquid phase was significant in biotrickling filters used for diethylether removal from off-gas [21]. Controlling water content at an appropriate range is necessary for maintaining a good mass transfer.

In a biofilter, water is removed rapidly because of the incomplete humidification of inlet stream and metabolic heat generated through pollutant oxidation [22]. The loss rate of water increases as temperature increases; as a result, thermophilic biofilters experience difficulty in regulating the water content of packing materials. However, the importance of water content in a thermophilic biofilter has been rarely described.

In present study, a thermophilic biofilter was investigated by varying the water contents (WCRs) of packing materials. The microbial populations in the biofilter during different irrigation interval time were assay and compared by applying polymerase chain reaction–denaturing gradient gel electrophoresis (PCR–DGGE). The transfer of oxygen in packing materials was determined by using microelectrodes. This study aimed to determine the effects of water content on biofilter performance and microbial population and to establish an efficient irrigation method for thermophilic biofilter treating off-gas.

2. Materials and methods

2.1. Experiment and procedures

A thermophilic biofilter composed of stainless steel with a height of 30 cm and a diameter of 10 cm was used in this study (Fig. 1). SO_2 was utilized as a target compound. Off-gases containing SO_2 generated from the thermal conversion processing of fuels in power plants, refineries, coal- and oil-fired boilers, and paper pulp production, are harmful to the environment and human health [4].

Table 1

Irrigation interval time, irrigation volume, irrigation duration and operation time.

No.	SI-7	SI-5	SI-3	SI-1	SI-0
Irrigation interval time (day)	7	5	3	1	Continuous
Irrigation volume (mL)	500	500	500	500	500
Irrigation duration time(min)	30	30	30	30	–
Operation time (month)	2	2	2	2	2

SI: Irrigation interval; SI-7: The irrigation interval time was 7 days; SI-5: The irrigation interval time was 5 days; SI-3: The irrigation interval time was 3 days; SI-1: The biofilter was irrigated everyday; SI-0: The biofilter was irrigated continuously.

Polyurethane foam cubes (PUFCs) were selected as packing materials for microbial attachment. The volume of each cube was about 1.0 cm^3 which was the same size with that for oxygen distribution analysis. The filling rate of PUFC in biofilter was $15\text{--}18 \text{ kg/m}^3$. SO_2 was supplied by a high-pressure cylinder. Then, 1% of SO_2 was diluted in proportion with air, and the average concentration in the inlet stream was $100\text{--}200 \text{ mg/m}^3$. The total flow rate was $0.6 \text{ m}^3/\text{h}$, which controlled by a calibrated mass flow meter. The corresponding empty bed residence time was 18 s. The outer surface of the biofilter column was wrapped around the heating belt to maintain the temperature at 60°C . As a result, the gas flowing through the biofilter was heated to $50\text{--}55^\circ\text{C}$. Inoculated microorganisms were collected from a thermophilic biofilter that treat off-gases contained SO_2 . The biofilter was operated at temperature of $55\text{--}60^\circ\text{C}$ and its gas handling capacity was $2900\text{--}3100 \text{ m}^3/\text{h}$. Methods for sulfur bacteria enrichment and acclimating were described in previous report [23]. Three sampling ports were set along the biofilter column to determine the SO_2 concentrations before (sample port 1 in Fig. 1) and after (sample port 3 in Fig. 1) the treatment and for microbiological analysis (sample port 2 in Fig. 1). A mineral nutrient solution with 5 g/L beef extract, 2.0 g/L K_2HPO_4 , 2.0 g/L KNO_3 , 0.01 g/L $\text{FeCl}_2 \cdot 4\text{H}_2\text{O}$, 1.0 g/L NaHCO_3 , 0.1 g/L $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, and 0.5 g/L NH_4Cl was periodically irrigated into the biofilter to sustain water and supply nutrients. Table 1 summarizes the irrigation interval times and irrigation volumes set in this study.

Fig. 1. The schematic diagram of the thermophilic biofilter. 1: High-pressure cylinder; 2: Mass flow meter; 3: Air pump; 4: Sample port 1: Inlet sampling point; 5: Biofiltration column; 6: Packing layer; 7: Thermostat; 8: Heating belt; 9: Sample port 2: Packing sampling point; 10: Sample port 3: Outlet sampling point; 11: Sprinkler; 12: Circulating pool; and 13: Water pump, 14: Inside of thermophilic biofilter.

Fig. 2. The schematic diagram of oxygen distribution analysis.

2.2. Chemical analysis

SO₂ was monitored online by using a flue gas analyzer (rbr, Ecom-J2KN, Germany). The removal efficiency of SO₂ was determined on the basis of SO₂ inlet and outlet concentrations [Eq. (1)]. Sulfate concentrations in the liquid phase were evaluated with an ion chromatogram analyzer (ICS-1000, Dionex ion chromatography system, USA). After 15 mins of irrigation, several PUFC cubes were collected from the biofilter bed for the determination of WCR. The WCR of packing materials was the average of several samples and was determined through gravimetry [Eq. (2)]. The temperature and relative humidity (RH) in the biofilter were recorded by using a Dewpoint thermohygrometer (WD-35612, OAKTON, Germany). The pH of the liquid was detected with a pH meter (pH-3C, Shanghai, China).

$$R = (C_{in} - C_{out}) \times 100 / C_{in} \quad (1)$$

$$WCR = \frac{(m_1 - m_2)}{m_1} \times 100\% \quad (2)$$

where R is the removal efficiency (%), C_{in} is the inlet concentration of SO₂ (mg/m³), C_{out} is the outlet concentration of SO₂ (mg/m³), m_1 is the mass of the moisture packing material, and m_2 is the mass of the dry packing material.

2.3. Oxygen distribution in PUFCs

PUFC was placed in a 630 mL organic glass tank (Fig. S1 in the supplementary materials available on-line). Air was supplied by an air pump at a flow rate of 3 L/min. The corresponding empty bed residence time was the same as that of the thermophilic biofilter. The PUFC was fixed on the plate by two little pins. The distance between the bottom of the PUFC and the surface of the plate was about 2 mm in order to ensure that the air could be supplied from the bottom side. The oxygen concentration on PUFCs was measured by a microelectrode with the tip diameter of 10 μm (OX-10, Unisense, Denmark). The oxygen distribution in four PUFC samples were investigated which have WCR of 98.08% (sample 1), 70.26% (sample 2), 20.70% (sample 3), and 2.3% (sample 4). The test was initiated at point AA and terminated at point BB (Fig. 2). The entire length of the detection in the PUFC was 12,000 μm, with a step of 100 μm per 7 s. It took 840 s to finish the detection.

2.4. Microbiological analysis

2.4.1. Medium for SO₂ degraders

Bacteria were incubated in a nutrient agar (BR, Aoboxing Biotech, Co., China) at 60 °C for 24 h. The sulfur bacteria were cultivated in a medium containing 2.0 g/L K₂HPO₄, 2.0 g/L KNO₃, 0.01 g/L FeCl₂·4H₂O, 1.0 g/L NaHCO₃, 0.1 g/L MgCl₄·6H₂O, 0.5 g/L NH₄Cl, and 5.0 g/L Na₂S₂O₃·5H₂O at 60 °C for 3 days. Cell counts were reported as colony-forming units (CFU).

2.4.2. DNA extraction

Total DNA was extracted by using an activated sludge DNA automatic plate form for Magnetic System-16 (TanBead, TaiWan). Afterward, DNA bands were verified through 1.0% agarose gel electrophoresis (Bio-Rad, USA). The concentrations of extracted DNAs were 30–60 ng/μL.

2.4.3. PCR-DGGE

PCR was conducted by using a C1000TM thermal cycler (Bio-Rad, USA). The V3 regions of the bacterial 16S ribosomal RNA gene of microbial samples were amplified by using two specific universal primers: F357 with a GC clamp and R517 (F357GC: 5'-CGCCCGCCGCGCGCGGGCGGGCGGGGACAGGGGGGCTACGGGAGGCAGCAG-3', R517: 5'-ATTACCGCGGCTGCTGG-3'). In each 50 μL reaction volume, 5 μL of the extracted DNA was mixed with 5 μL of 10 × Ex Taq buffer (Mg²⁺ Plus), 4 μL of dNTPs, 1 μL of the primers (10 μM), and 1.5 U of Ex Taq polymerase (TaKaRa, Dalian, China). The reaction condition of PCR was based on a previous study [24]. DGGE was performed on 8% (W/V) polyacrylamide gel with 40%–60% denaturing gradient of denaturants. Electrophoresis was carried out for 960 min at a constant voltage of 65 V and temperature of 60 °C. The gels were stained with SYBER Green I. Digital images were captured by using Fluor-S MultiImager (Gel Doc XR, Bio-Rad, USA) and analyzed with Quantity One (Bio-Rad, USA).

2.4.4. Sequencing and phylogenetic analysis

Bacterial diversity was estimated on the basis of the intensity and number of bands by using Shannon's index (H). The 16S rRNA gene sequences from DGGE bands were analyzed on the basis of Nucleotide–Nucleotide BLAST (Blastn) database, Seqmatch program, and chimera check program of the Ribosomal Database Project. The sequences and their closest matches retrieved from the

Fig. 3. The irrigation interval time on SO_2 removal efficiency. RE: removal efficiency; CT: irrigation continuously.

databases were aligned using Clustal X version 1.8. Phylogenetic trees were constructed using a neighbor-joining method in MEGA 6.1. The evolutionary distances of nucleotide sequences were calculated with a Kimura 2-parameter model; bootstrap values were obtained with 1000 resamplings.

3. Results and discussion

3.1. Effects of irrigation interval on biofilter performance

Thermophilic biofilter had been carried out for over 10 months to investigate the biofilter performance. The flow rate and temperature were maintained at $0.6 \text{ m}^3/\text{h}$ and 60°C , respectively. The inlet concentrations of SO_2 ranged from $100.0 \text{ mg}/\text{m}^3$ to $200.0 \text{ mg}/\text{m}^3$. The thermophilic biofilter achieved an average SO_2 removal efficiency of 94.38%. A maximum elimination capacity of $50.67 \text{ g}/\text{m}^3 \cdot \text{h}$ was obtained at an SO_2 inlet concentration of $199 \text{ mg}/\text{m}^3$. Therefore, the thermophilic biofilter could be used to treat SO_2 effectively.

After 2 months of operation, the irrigation interval time was reduced step-by-step from 7 days to 1 day to investigate the effects of irrigation on biofilter performance. The average removal efficiency of SO_2 was approximately 60% when the irrigation interval time was 7 days (Fig. 3). When the biofilter was irrigated daily or continuously, over 90% removal efficiency of SO_2 could be achieved. The removal efficiency was influenced by the period of irrigation interval. SO_2 removal efficiency increased gradually with the increasing of irrigation frequency.

The WCR of PUFC varied with irrigation interval time (Fig. 4). The WCR of PUFC sharply decreased from 85.55% to 5.57%, with an average decreasing rate of 13% per day, when the irrigation interval was 7 days (RE-7 in Fig. 4a). By comparison, a decreasing rate of 2% is observed in a mesophilic (20°C – 30°C) biofilter for SO_2 removal [25]. In our study, the temperature of the column was maintained at 60°C . The decreasing speed of WCR was faster than that of the mesophilic biofilter. Conversely, >80% WCR in PUFC was maintained when the thermophilic biofilter was irrigated daily or continuously (RE-1 in Fig. 4b). The removal efficiencies decreased obviously as the WCR was reduced (WCR-7 in Fig. 4a). Over 99% of SO_2 removal could be achieved when the WCR in PUFC was as high as 85% (RE-1 in Fig. 4b). The change of SO_2 removal efficiency was caused by water content variation. SO_2 removal efficiency obviously decreased from 90% to 60% when the water content of packing materials is reduced from 80% to 30% (Fig. 5). This result was consistent with previous reports [14,15].

Fig. 4. (a) SO_2 removal efficiency and WCR of PUFC at irrigation interval time of 7 days, WCR-7: water content at irrigation interval time of 7 days; RE: removal efficiency, (b) SO_2 removal efficiency and WCR of PUFC at continuous irrigation, WCR-1: water content at daily irrigation; RE: removal efficiency.

The previous reports of SO_2 transformation in the thermophilic biofilter showed that SO_2 reduction involves biodegradation by microorganisms, dissolution in the aqueous phase, and adsorption by packing materials and microorganisms [26]. Among these processes, microbial degradation played the most important role, and a large proportion of SO_2 was biooxidized into SO_4^{2-} [26]. SO_2 is a water-soluble compound, and approximately $32 \text{ g}/\text{L}$ of SO_2 can be dissolved in liquid at 60°C . High WCR promotes the transfer of SO_2 from a gaseous phase to a liquid phase. SO_2 in the liquid phase can be utilized by microorganisms. Therefore, optimum WCR was needed for substrate dissolution, microbial growth and activity maintenance. In addition, the pH gradually decreased from 6.5 to 3.0 as H_2SO_4 was formed within one irrigation period (7 days) (Fig. 6). When less irrigation was applied, the accumulation of H^+

Fig. 5. WCR of PUFC on SO_2 removal efficiency.

Fig. 6. pH and sulfate variation within one irrigation period (7days).

and SO_4^{2-} took place. The accumulation of sulfuric acid may also lead to a reduction in the removal efficiency. Frequent irrigation can avoid the accumulation of acid. To maintain the ideal water content ($\geq 80\%$) for optimal operation of a biofilter, irrigation occurred every day in the present study.

3.2. WCR on oxygen distributions in PUFCs

After SO_2 dissolves in water, SO_3^{2-} is produced then biooxidized to SO_4^{2-} [Eqs. (3) and (4)] [27]. There were 4.76–36.8 g/L of SO_4^{2-} were determined from the biofilter in the present study. Oxygen is an important component of SO_2 transformation. Microorganisms obtain energy for their growth through respiration in the presence of oxygen [28]. It is necessary to detect the oxygen in packing material which were packed in the thermophilic biofilter.

Oxygen distributions in PUFCs at various WCRs are shown in Fig. 5. The oxygen concentrations were initially determined at position AA along the route (Fig. 7). The oxygen concentration in the surrounding air was 10.7 mg/L. The oxygen concentration gradually decreased from the surface to the center of PUFC when the WCR of PUFC was 98.08% (Fig. 7a). The distribution of oxygen presented aerobic-low oxygen-aerobic states along the test route on PUFC-1 at 98.08% WCR. A similar phenomenon occurred on PUFCs-1 at 70% WCR (Fig. 7b). The oxygen concentrations slightly changed from the PUFC surface to the center when WCR decreased to 55% (Fig. 7c). Then, the oxygen concentrations became evenly when WCR was 2.3% (Fig. 7d). Results indicated that oxygen concentrations varied

with changes in WCR. The oxygen concentration changed remarkably in the PUFC with a high WCR. Oxygen was distributed evenly along the test route in the PUFCs with a low WCR.

The transfer of oxygen from air to liquid can be divided into two processes: surface oxygen transfer and liquid film diffusion. Surface oxygen transfer occurs at the air-water interface. The diffusion rate of oxygen in water is only one tenth-thousandth of that in air [29]. As a polar molecule, oxygen is poorly soluble in water; as a consequence, oxygen transfer through the liquid-gas surface and diffusion in liquid are inhibited. This finding indicated that water was possibly accounted for the discrepancy of oxygen distribution in a PUFC. A low oxygen concentration was detected when WCR was $>70\%$. Oxygen was evenly distributed on the PUFC with $<20\%$ WCR in the thermophilic biofilter.

3.3. Effects of irrigation interval on microbial population

PUFCs were collected periodically from the thermophilic biofilter to investigate the effect of irrigation intervals on microbial populations. Table 2 shows the number of total bacteria (TB) and total sulfur bacteria (TSB) of PUFC at different irrigation interval times. An increase in the amount of TB and TSB coincided with the decreasing of the irrigation interval time. The WCR of PUFC was maintained 80.2–91.0% when the biofilter was irrigated daily or continuously. This condition could be beneficial for microbial survival and activity. SO_2 was dissolved in liquid and then biodegraded which provide substrate and energy for microbial growth. The maximum amount of TSB and ratio of TSB/TB could be obtained when the biofilter was irrigated every day which resulted in high SO_2 removal efficiency.

DGGE was used to explore the microbial population in PUFCs with different WCRs. Shannon's index was used to indicate the individual biodiversity of the bacterial groups (Fig. 8). The diversity of bacteria increased in the PUFC as irrigation interval time was shortened from 5 days to 1 day. By comparison, bacterial diversity remained unchanged when the thermophilic biofilter was irrigated daily and continuously. With the irrigation frequency increasing, the diversity of bacteria increased as well as the amount of bacteria.

Twenty-five discriminable bands (B1 to B25) were identified, and their sequences were matched with their closest relatives in GenBank (Table 3). Eight bands (B4, B10, B16, B18, B20, B21, B22, and B23) emerged in all of the samples whose WCR varied from 25.57% to 91.02%. Band B4 was closely related to *Enterococcus faecium* T1 (99%). *Enterococcus* species are facultative anaerobes that can tolerate extreme temperatures (10°C – 45°C) [30]. Bands B10 and B18 belonged to *Virgibacillus* sp. FJAT-22389 (100%).

Fig. 7. Oxygen distributions in PUFCs. (a) PUFC containing 98.08% of WCR, (b) PUFC containing 70.26% of WCR, (c) PUFC containing 54.98% of WCR, (d) PUFC containing 2.30% of WCR.

Table 2

The amount of bacteria and sulfur bacteria in the biofilter.

No.	SI-7	SI-5	SI-3	SI-1	SI-0
WCR (%)	25.57	46.31	71.49	85.42	91.02
TB (CFU/mL)	$2.28 \pm 0.31 \times 10^{10}$	$2.94 \pm 0.96 \times 10^{10}$	$3.54 \pm 0.23 \times 10^{10}$	$5.70 \pm 0.36 \times 10^{11}$	$3.07 \pm 0.57 \times 10^{11}$
TSB (CFU/mL)	$6.93 \pm 0.85 \times 10^7$	$1.01 \pm 0.49 \times 10^8$	$1.76 \pm 0.58 \times 10^8$	$3.46 \pm 0.37 \times 10^9$	$1.78 \pm 0.11 \times 10^9$
R	0.30	0.34	0.50	0.61	0.58

TB: Total bacteria; TSB: Total sulfur bacteria; R: Ratio; R = TSB/TB $\times$ 100(%).

Virgibacillus species can be enriched in a sulfur-containing medium and use thiosulfate as an electron acceptor [31]. Band B20 was closely associated with *Arthrobacter creatinolyticus* V1R2A1 (99%), which can degrade organic sulfur-containing aromatic compounds [32]. Bands B16, B21, B22 and B23 belonged to *Bacillus* sp., which is often involved in sulfur odor treatment at high temperatures [33]. These bacteria are thermophilic bacteria or desulfurization bacteria. Microbial growth is a consequence of the uptake and metabolism of air pollutants. SO₂ in the inlet stream functions as an energy source and building material. During the operation, the temperature of the biofilter was maintained at 60 °C. Desulfurization and thermophilic bacteria can vigorously grow in an environment with an abundant SO₂ supply and 60 °C temperature; these conditions in turn maintained the efficiency of the biofilter.

Bands B6, B8, B12, B17, and B25 were present in the lanes of SI-7 and SI-5 but were absent in other lanes. Their closest relatives were *Psychrobacter pulmonis* WD817 (B6), *Sphingobacteriales* bacterium ARUP UnID 327 (B8), *Stenotrophomonas humi* D2 (B12), *Pseudogracilibacillus auburnensis* P-207 (B17), and *Aneurinibacillus* sp. G5 (B25), respectively. These strains were all obligate aerobes. *Psychrobacter pulmonis* is an aerobe that can grow at >40 °C. *Sphingobacteriales* sp. can oxidize sulfide to elemental sulfur in membrane bioreactors [34]. *Stenotrophomonas* sp. is strictly aerobic and can utilize dibenzothiophene as an exclusive sulfur source [35]. *Pseudogracilibacillus auburnensis* is an aerobic endospore-forming bacterium that can grow in high-temperature environments. *Aneurinibacillus* sp. is usually isolated from sludge in high-temperature environments and can degrade sulfide in bioreactors

[36]. The WCRs of SI-7 and SI-5 were 25.57% and 46.31%, respectively. These strictly aerobic bacteria existed in packing materials with WCRs of <50%.

Bands B2, B3, B5, B11, B14, B15, and B19 were detected in the lanes of SI-3, SI-1, and SI-0. The closest relatives of these bands were *Sporosarcina* sp. J1-9F (B2 and B15), *Staphylococcus equorum* KS1039 (B3), *Carnobacterium* sp. 12266/2009 (B5), *Castellaniella* sp. SJC14 (B11), *Virgibacillus* sp. AS10 (B14), and *Paenibacillus* sp. LB220 (B19), respectively. They were all facultative anaerobes that can undergo metabolism in the absence of oxygen [37,38]. The WCRs of SI-3, SI-1, and SI-0 were 71.49%, 85.42%, and 91.02%, respectively. These facultative anaerobic bacteria appeared in the packing materials whose WCR was >70%. When the WCR was as high as 70%, below 2 mg/L of the oxygen concentration presented in the center of the PUFC which resulted in the appearance of facultative anaerobic bacteria.

Desulfurization and thermophilic bacteria were abundant in the biofilter. More obligate aerobic bacteria were found in packing materials with low WCR. Facultative anaerobic bacteria increased obviously at high WCR when the biofilter was irrigated frequently. The ratio of FAB to TB increased from 30.76% to 57.14% as the irrigation interval time was shortened (Table 4). Facultative anaerobic bacteria can undergo metabolism in the presence and absence of oxygen. When the biofilter was irrigated daily or continuously, the WCR of PUFC remained at >80% which led to the oxygen distribution uneven in PUFC. The oxygen concentration in some areas of PUFCs was <2 mg/L, at which level inhibited the growth of obligate aerobic bacteria. WCR influenced the oxygen distribution in PUFCs, and microbial populations consequently varied.

Table 3

The closest relatives and isolation sources of dominate bacteria.

Band no.	Closest relatives	Source	Similarity
B1, B6	<i>Psychrobacter pulmonis</i> WD817	Bacteria; Proteobacteria; Gammaproteobacteria; Pseudomonadales; Moraxellaceae; Psychrobacter.	100%
B2, B15	<i>Sporosarcina</i> sp. J1-9F	Bacteria; Firmicutes; Bacilli; Bacillales; Planococcaceae; Sporosarcina.	99%
B3	<i>Staphylococcus equorum</i> KS1039	Bacteria; Firmicutes; Bacilli; Bacillales; Staphylococcus.	100%
B4	<i>Enterococcus faecium</i> T1	Bacteria; Firmicutes; Bacilli; Lactobacillales; Enterococcaceae; Enterococcus.	99%
B5	<i>Carnobacterium</i> sp. 12266/2009	Bacteria; Firmicutes; Bacilli; Lactobacillales; Carnobacteriaceae; Carnobacterium.	100%
B7	<i>Proteus</i> sp. LW-18	Bacteria; Proteobacteria; Gammaproteobacteria; Enterobacteriales; Enterobacteriaceae; Proteus.	100%
B8	<i>Sphingobacteriales</i> bacterium ARUP UnID 327	Bacteria; Bacteroidetes; Sphingobacteriia; Sphingobacteriales.	100%
B9	<i>Lactococcus lactis</i> OZK16	Bacteria; Firmicutes; Bacilli; Lactobacillales; Streptococcaceae; Lactococcus.	100%
B10, B18	<i>Virgibacillus</i> sp. FJAT-22389	Bacteria; Firmicutes; Bacilli; Bacillales; Bacillaceae; Virgibacillus.	100%
B11	<i>Castellaniella</i> sp. SJC14	Bacteria; Proteobacteria; Betaproteobacteria; Burkholderiales; Alcaligenaceae; Castellaniella.	98%
B12	<i>Stenotrophomonas humi</i> D2	Bacteria; Proteobacteria; Gammaproteobacteria; Xanthomonadales; Xanthomonadaceae; Stenotrophomonas.	100%
B13	<i>Bacillus cereus</i> HYM90	Bacteria; Firmicutes; Bacilli; Bacillales; Bacillaceae; Bacillus; Bacillus cereus group.	100%
B14	<i>Virgibacillus</i> sp. AS10	Bacteria; Firmicutes; Bacilli; Bacillales; Bacillaceae; Virgibacillus.	100%
B16, B23	<i>Bacillus firmus</i> UM034Bf	Bacteria; Firmicutes; Bacilli; Bacillales; Bacillaceae; Bacillus.	100%
B17	<i>Pseudogracilibacillus auburnensis</i> P-207	Bacteria; Firmicutes; Bacilli; Bacillales; Bacillaceae; Pseudogracilibacillus.	100%
B19	<i>Paenibacillus</i> sp. LB220	Bacteria; Firmicutes; Bacilli; Bacillales; Paenibacillaceae; Paenibacillus.	100%
B20	<i>Arthrobacter creatinolyticus</i> V1R2A1	Bacteria; Actinobacteria; Micrococcales; Micrococcaceae; Arthrobacter.	99%
B21, B22	<i>Bacillus thermophilus</i> SgZ-10	Bacteria; Firmicutes; Bacilli; Bacillales; Bacillaceae; Bacillus.	100%
B24	<i>Pusillimonas terrae</i> EGY-WCP1	Bacteria; Proteobacteria; Betaproteobacteria; Burkholderiales; Alcaligenaceae; Parapusillimonas.	99%
B25	<i>Aneurinibacillus</i> sp. G5	Bacteria; Firmicutes; Bacilli; Bacillales; Paenibacillaceae; Aneurinibacillus group; Aneurinibacillus.	100%

Fig. 8. DGE profile and Shannon indices of bacterial community.

Table 4

The specie of bacteria and facultative anaerobic bacteria in the biofilter.

No.	SI-7	SI-5	SI-3	SI-1	SI-0
TB (species)	16	13	16	21	19
FAB (species)	5	4	6	12	10
R = FAB/TB × 100(%)	31.25	30.76	37.5	57.14	52.63

TB: Total bacteria; FAB: Facultative anaerobic bacteria; R: Ratio.

4. Conclusions

The WCR of PUFCs increased as irrigation interval time was shortened. At a WCR of >70%, the distribution of oxygen exhibited aerobic-low oxygen-aerobic states in PUFCs. Oxygen was evenly distributed when the WCR was <55%. Oxygen distributions differed in the PUFCs, and the distribution of microorganisms varied accordingly. For the efficient SO₂ removal by using thermophilic biofilters, the optimum WCR was >80%, which can be achieved by daily irrigation. Pressure decreased remarkably in the bioreactor with excess irrigation, and this phenomenon may consume excessive energy. Therefore, porous packing materials could be help maintain appropriate WCR and prevent high energy consumption.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.bej.2016.11.015>.

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