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TUBULAR BIOFILTER TREATMENT OF ISOBUTANOL EMISSIONS UNDER VARIOUS ORGANIC LOADING RATES

Isobutanol in waste gas streams was treated by a tubular biofilter (TBF) which continuously operated for 364 days under various organic loading rate (*OLR*) from 11 g·m^{-3}·h^{-1} to 66 g·m^{-3}·h^{-1}. Results show that within 60 days, the TBF successfully started up even after changing the *OLR* from 31.3 to 15.6 g·m^{-3}·h^{-1}. The average removal efficiencies (*RE*s) were totally higher than 90% when *OLR*s ranged from 12.14 to 66.45 g·m^{-3}·h^{-1}. Two distinct performance deterioration periods were observed at days 186–253 and days 280–334, both of which recovered without additional measurement. During these periods, the larvae and adult moth flies, been identified as *Psychodinae* infested the TBF, greatly affected the TBF performance. When the number of adult *Psychodinae* decreased, TBF performance recovered. The elimination capacity (*EC*) was 60.42 g·m^{-3}·h^{-1} at the inlet *OLR* of 66.45 g·m^{-3}·h^{-1}, with the critical *EC* being around 50 g·m^{-3}·h^{-1}. Even under a low gas empty bed residence time of 15 s, the preferable *RE*s and *EC*s under middle or low *OLR*s were still obtained by the TBF.

SYMBOLS

C_{Gi} – inlet isobutanol concentration, g·m^{-3}
C_{Go} – outlet isobutanol concentration, g·m^{-3}
EBRT – empty bed residence time, s
EC – elimination capacity, g·m^{-3}·h^{-1}
n – number of operation days, day
OLR – organic loading rate, g·m^{-3}·h^{-1}
PD-P – performance deterioration periods
Q – inlet gas flow rate (volumetric), m^3·h^{-1}
RE/η – removal efficiency, %
TBF – tubular biofilter
V_f – apparent volume of the filter media, m^3

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1. INTRODUCTION

Biofiltration has been successfully used to remove volatile organic compounds (VOCs) from waste gas streams [1]. For decades, many researchers have focused on improving the efficiency of biofilters and expanding scopes of its application [2, 3]. Meanwhile, the effects of filter media [3, 4] microorganisms [5, 6] and other operational conditions associated with pollutant removal mechanisms [7, 8] were thoroughly investigated. However, some challenges such as large footprints, declining performance through time, and continuous operation still limit the widespread use of both traditional biofilters and biotrickling filters [1, 9].

Biofilters require large footprints due to their longer gas empty bed residence time (*EBRT*) compared to other reactors. Moreover, biofilter performance often declines due to excessive biomass accumulation in the filter media over extended periods of operation [10]. To resolve these issues, recent efforts have now focused on the development of new biofilters to enhance removal of pollutants from waste gas streams, such as new suspended biofilter [11], rotating drum biofilter (RDB) [12, 13], rotating rope biofilter [14], modified rotating biological contactor [15], rotating biological filter [16] and tubular biofilter (TBF) [17]. Among these new technologies, the TBF seems to be the most promising. Constructing by a closed chamber, a module polyurethane sponge tube, and a nutrient solution distributor, the TBF has shown good long-term operation performances for toluene and methyl isobutyl ketone (MIBK) removal with little excessive biomass accumulation in the filter media [17, 18]. Although our previous studies focused on the treatment of toluene and MIBK even at high gas flow rates and over long operation periods by the TBF, further investigations on the removal characteristics and process mechanisms of other kinds of VOCs from waste gases are still needed.

Isobutanol (isobutyl alcohol) is widely used in industries as a chemical intermediate and as a solvent in coating applications. Meanwhile, isobutanol can cause serious environment pollution such as crop death, risk of explosion when mixed with air (explosion limit 2.5 vol. % and impairing human health [19, 20]. Compared with toluene with the octanol/water partition coefficient of 4.0, isobutanol is of a low octanol/water partition coefficient ($\log P_{ow} = 0.8$). Due to their good hydrophilicity and biodegradability, butanols were degraded by the biofilter or the biotrickling filter [21–24]. However, the maximum elimination capacities (*EC*s) of butanols were reportedly not higher than 56 $g \cdot C \cdot h^{-1}\ m^{-3}$ bed volume, which means that much improvement is still needed.

To promote the purification performance of isobutanol emissions, a lab-scale TBF was continuously operated for 364 days under organic loading rates (*OLR*s) from 11.0 to 62.6 $g \cdot m^{-3} \cdot h^{-1}$. The effects of organic loading rate on isobutanol removal efficiency and *EC*s were investigated. The deterioration and recovery of the TBF performance were also explored in this study.

2. MATERIALS AND METHODS

Experimental apparatus. A TBF developed in our previous study [17] was used to assemble the experimental system in this study, consisting of a closed chamber, a module tube of polyurethane sponges and a nutrient solution distributor. The closed cylindrical chamber had an inner diameter of 16 cm and a height of 15 cm, which was composed of a Plexiglas pipe with two perforated Plexiglas plates at both ends. The nutrient solution distributor, impermeable for waste gases, included two nutrient feeding channels and a horizontal perforated plate for the uniform distribution of liquid. A module of tubular and open-pore reticulated polyurethane sponges (Shenzhen Jiechun Filter Material Co., Ltd., Guangdong, China) was perpendicularly mounted in the center of the closed cylindrical chamber located between the nutrient solution distributor and the bottom of the chamber. The porosity and pore size of the sponges were 98% and approximately 12 pores per centimeter (30 PPI), respectively. The module tube of polyurethane sponges had an outer diameter of 14 cm, a radial thickness of 3 cm and a height of 10 cm.

Waste gases entered the TBF through the gas inlet located at the center of the top surface of the chamber and flowed over the nutrient solution distributor before passing through the module polyurethane sponge tube. Pollutants from waste gases were biodegraded by the attached microorganisms on the media. The purified gas was discharged by the gas outlet located at the center at the bottom of the chamber. At the same time, nutrient solutions were pumped into the TBF, which were uniformly distributed on the media by the nutrient solution distributor. With a supply of nutrient solution at a rate of 6.0 $dm^3 \cdot day^{-1}$, a nutrient solution tank for regeneration and circulation collected the effluents from the bottom of the chamber. The experimental apparatus has been described in detail elsewhere [17].

Operational procedures. A freshly prepared tubular media was immersed in clean water for 2 days. Subsequently, it was placed in the activated sludge to allow the proliferation of the TBF microbial community for a week, and then taken out and mounted onto TBF. After this, the synthetic waste gas and nutrient solution were introduced into the TBF. When the media was introduced into the biofilter, it was considered the initial time of TBF operation (day 1).

With an initial startup stage in days 1–60, the TBF was operated on various *OLR*s without the reference from day 1 to day 263, while in days 264–364, the reference condition was set at *OLR* of 21.9 $g \cdot m^{-3} \cdot h^{-1}$ (run VII) to track the reproducibility and pseudo--steady-state condition of the TBF. For the entire duration of the operation, a gas *EBRT* of 15 s remained unchanged. The operation conditions implemented in this study are listed in Table 1. The TBF was kept gas-proof except for biological observations on day 339, and the biomass accumulation in the filter media was never wiped out during the entire year (364 days) of operations.

Table 1

Operation conditions of the TBF for isobutanol removal

Run No.	Time [day]	*OLR* [$g\cdot m^{-3}\cdot h^{-1}$]	C_0 [$mg\cdot m^{-3}$]	*EBRT* [s]
I-1, I-2, I-3	0–41, 112–126, 148–178	31.3	134	15
II-1, II-2, II-3	42–60, 105–111, 136–147	15.6	67	15
III-1, III-2, III-3, III-4	61–69, 92–104, 127–135, 226–263	46.9	201	15
IV	70–91	62.6	278	15
V-1, V-2	179–190, 271–347	43.8	184	15
VI	191–225	12.5	53	15
VII-1, VII-2, VII-3	264–270, 348–355, 361–364	21.9	92	15
VIII-1	356–360	11.0	46	15

C_0 is the inlet isobutanol concentration.

Chemical and biological materials. Analytical isobutanol (99%, Damao Chemical Industry Co., Tianjin, China) was used as the target contaminant in preparing the model waste gases. Clean air and the injected isobutanol were mixed to synthesize the waste gas stream. The concentrations of isobutanol in the synthetic waste gases were adjusted by changing the flow rate of the clean air stream and the amount of neat isobutanol vapor. Similarly, analytical reagents were used to prepare nutrient solutions. The fresh activated sludge used for seeding the TBF was taken from a secondary sedimentation tank of a municipal wastewater treatment plant (Changsha Guozhen Wastewater Treatment Co., Ltd., Hunan, China).

Analytical methods. Gas-phase measurements included isobutanol concentrations in the influent and effluent gas streams for the TBF. Isobutanol concentrations in the gas samples collected daily were determined by a gas chromatograph (GC) (HP 6890N, Series II, Hewlett-Packard, Palo Alto, California, USA), equipped with a flame ionization detector and with an HP-VOC capillary column (60 m × 320 μm ID × 1.8 μm, Agilent, USA). Highly pure nitrogen gas (99.9%) was employed as the carrier gas and was supplied at a flow rate of 30 $cm^3\cdot min^{-1}$, while the temperatures at the GC injector, oven, and detector were set up at 120, 120, and 250 °C, respectively.

The whole experiment was conducted in Changsha city, located in the middle-south of China with a subtropical climate. A thermometer (Boli Thermometer, Baling Instrument Plant, Yueyang, China) was used to measure the ambient temperature of the laboratory. The collected data, including the removal efficiency (*RE*) and the ambient temperature, were determined using an OriginPro2015 (OriginLab Co.). On day 339, the TBF was dismantled to investigate biological succession and was photographed with a digital camera (Canon Ixus 80 IS, Canon China Co., Ltd., Shenzhen, China). To further analyze the flies that appeared in the chamber, we also did manual counting.

Calculations. The *OLR* is the mass loading rate (volumetric and expressed as $g \cdot m^{-3} \cdot h^{-1}$), which was determined from the mass of the contaminant entering the biofilter per unit volume of the filter material per unit time.

$$OLR = \frac{Q_{Gi}}{V_f} \tag{1}$$

where Q_{Gi} is the inlet gas flow rate, $m^3 \cdot h^{-1}$, and V_f is the apparent volume of the filter media, m^3.

Gas *EBRT* was defined as the empty bed filter volume divided by the airflow rate:

$$EBRT = \frac{V_f}{Q} \tag{2}$$

Further, Q is the fraction of the contaminant removed by the TBF (*RE*), %.

$$\eta = \frac{C_{Gi} - C_{Go}}{C_{Gi}} \times 100\% \tag{3}$$

where, η is the *RE*, and C_{Go} is the outlet isobutanol concentration, $mg \cdot m^{-3}$. When the TBF stabilized at a high-performance level in an operation period, the average *RE* was calculated as follows.

$$\overline{\eta} = \frac{\eta_1 + \eta_2 + \ldots + \eta_n}{n} \tag{4}$$

where, $\overline{\eta}$ is the average *RE*, %, and n is the number of days when TBF achieved a steady-state within a certain operation period, day.

The *EC*, $g \cdot m^{-3} \cdot h^{-1}$, is the amount of pollutant degraded per unit of time, normalized by the volume of the packed bed.

$$EC = \frac{\left(C_{Gi} - C_{G0}\right)}{V_f} \times Q \tag{5}$$

Furthermore, the maximum *EC* (EC_{max}) is defined as the maximum removal percentage of isobutanol regardless of the employed *OLR*s, whereas the critical load is defined as the minimum *OLR* for which the TBF reached its maximum *EC* [18].

3. RESULTS AND DISCUSSION

3.1. TBF PERFORMANCE DURING THE STARTUP STAGE

The TBF started and operated for 60 days under a gas *EBRT* of 15 s, and it maintained *OLR*s of 31.3 g·m^{-3}·h^{-1} for days 1–41 (run I-1) and 15.6 g·m^{-3}·h^{-1} during days 42–60 (run II-1). The results are illustrated in Fig. 1.

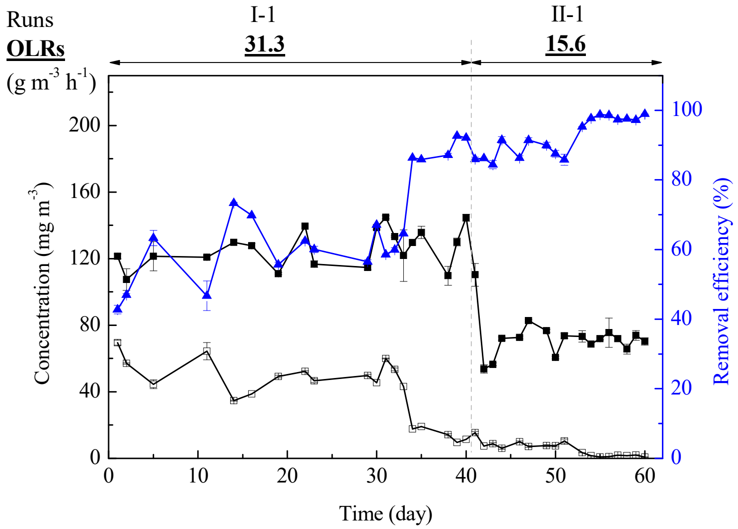

Fig. 1. TBF performance on the startup stage: ■ – inlet isobutanol concentration, □ – outlet isobutanol concentration, ▲ – isobutanol removal efficiency (*RE*)

The actual average concentrations of inlet isobutanol were 125.4 and 71.4 mg·m^{-3} for run I-1 and run II-1, respectively. At run I-1, the isobutanol *RE* first increased with time, which then reached over 85% after day 34 and to more than 92% on day 39. And then the corresponding isobutanol *RE* initially decreased to 86.3%, and subsequently increased to above 95.3% in the following 10 days, averaging to a *RE* of 98.3% in days 54–60. Figure 1 shows that no more than 60 days was needed for a successful startup of the TBF for isobutanol removal when *OLR* was changed from 31.3 g·m^{-3}·h^{-1} to 15.6 g·m^{-3}·h^{-1}.

When the TBF was used for toluene removal, the resulting *RE* was less than 90% until day 45 on the startup stage under an *OLR* of 21.9 g·m^{-3}·h^{-1} and a gas *EBRT* of 15 s [17]. Whereas, a shorter period was needed to achieve higher *RE* during the startup stage for isobutanol removal in this study. For toluene removal using a biotrickling filter with polyurethane sponge as filter media, the startup stage almost took 3–4 weeks [25]. Nevertheless, a long period for the startup of biofilters was shortened by modifying the technique such as by enhancing the mass transfer of pollutants, improving microbial populations, adding chemicals and optimizing operation conditions [26]. This allowed the TBF to be successfully started for isobutanol removal.

3.2. EFFECT OF ORGANIC LOADING RATE

Following the startup stage, the TBF was operated at various *OLR*s from 15.6 to 62.6 g·m^{-3}·h^{-1} in days 61–185. The results are illustrated in Fig. 2.

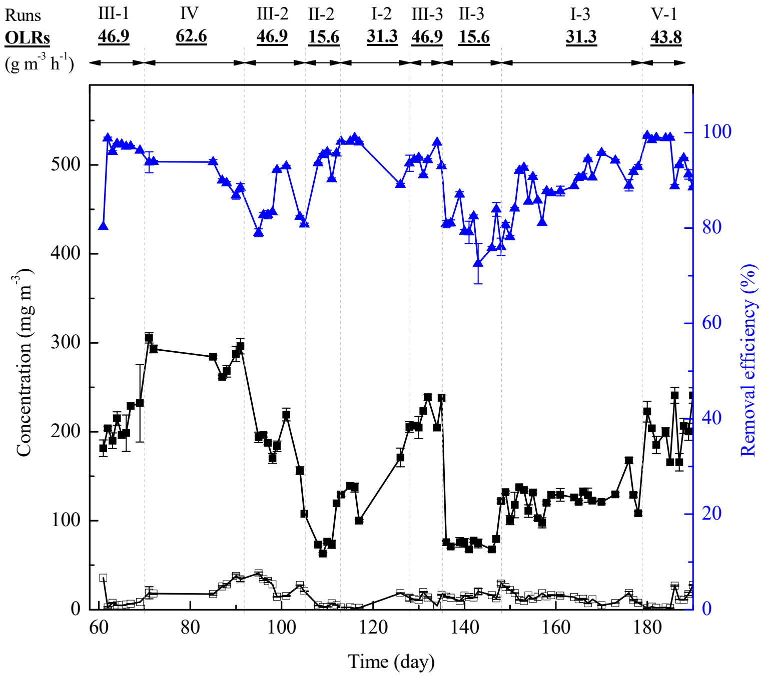

Fig. 2. Isobutanol *RE*s at various loading rates (*OLR*s):
■ – inlet concentration, □ – outlet concentration, ▲ – isobutanol *RE*

The average *RE* decreased with the increase of *OLR*. When *OLR* was changed, *RE* first decreased followed by a rapid increase before stabilizing at a high level. These observations were consistent with previous reports on *OLR* changes [21, 26]. The general *RE* was commonly over 80% at an inlet isobutanol concentration of 60–300 mg·m^{-3}, except for several days following the *OLR* changes. Even at run IV of the highest *OLR* of 62.6 g·m^{-3}·h^{-1}, the average removal efficiency was 90.9%. The outlet isobutanol concentrations were lower than 20 mg·m^{-3} when it reached steady states at various *OLR*s. Under small *OLR*s from 15.6 to 62.6 g·m^{-3}·h^{-1}, a short *EBRT* of 15 s that was applied to TBF was considered as a very efficient *EBRT* in biofiltration [13, 25]. In general, TBF was suitable for the removal of isobutanol from waste gases under low inlet concentrations and a short gas *EBRT* of 15 s.

For *n*-butanol, removal by a biotrickling filter, acceptable maximum inlet loading would be lower than 317.2 $g \cdot m^{-3} \cdot h^{-1}$ under *EBRT* of 30–80 s (at airflow rates of 3.5–9.5 $m^3 \cdot h^{-1}$ and a working volume of 75 dm^3) [24]. Chan and Lai [22] found that the *RE* of *n*-butanol was higher than that of isobutanol when applied to a biofilter for waste gas treatment because the compound with no side group in the main chain would be easier to be biodegraded by the microbial community [21]. Generally, a high *RE* could be obtained by prolonging the *EBRT* for the removal of VOCs using biofilters [13]. Therefore, the TBF performance could be improved by prolonging gas *EBRT*s or treating other VOCs that are easily biodegradable.

3.3. PERFORMANCE DETERIORATION AND RECOVERY

When *OLR*s increased from 15.6 to 43.8 in days 136–185, the *RE* increased from 80.2% to 95.1%, which was different when *OLR*s was increased from 15.6 to 46.9 in days 105–135 (Fig. 2). Moreover, two distinct performance deterioration periods (PD-P) emerged in days 186–253 (PD-P1) and in days 280–334 (PD-P2) under normal operating conditions as shown in Fig. 3.

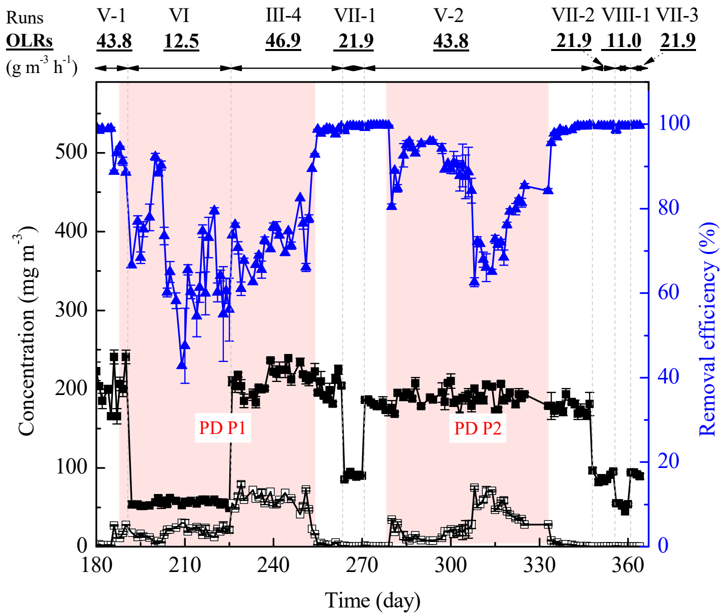

Fig. 3. Isobutanol removal under performance deterioration periods:
■ – inlet concentration, □ – outlet concentration, ▲ – isobutanol *RE*

During PD-P1, the *RE* dramatically decreased to 73.5% on day 203 (run V-1), then fluctuated violently between 50%–70% (run VI), and subsequently increased again to 89.5% on day 253 (run III-4). Whereas, during PD-P2 at an *OLR* of 43.8 $g \cdot m^{-3} \cdot h^{-1}$ (run V-2), the *RE* appeared to have alternating increase and decrease, before it finally gradually increased to 95.6% on day 334. Except for PD-P1 and P2, the *RE* was all more than 95% at the *OLR* of 46.9 $g \cdot m^{-3} \cdot h^{-1}$ (in days 254–263 during run III-4), 43.8 $g \cdot m^{-3} \cdot h^{-1}$ (in days 271–279 and 334–347 during run V-2), 21.9 $g \cdot m^{-3} \cdot h^{-1}$ (run VII-1, VII-2 and VII-3) and 11.0 $g \cdot m^{-3} \cdot h^{-1}$ (run VIII-1). Following PD-P1, the *RE* was higher than 97.5% (day 255–279) but was over 98.2% after PD-P2 (day 337–364) (Fig. 3).

Although the operational conditions were kept changed following the deterioration periods, the *RE* could automatically be raised to the previous high level. As shown in Fig. 3, the TBF performance could effectively recover by itself to an extreme high level either at changed *OLR*s (PD-P1) or at an unchanged *OLR* (PD-P2). During the entire operation period for 364 days, the other conditions, such as the filter media, gas *EBRT*, nutrients concentrations and its supplements were kept unchanged. It was difficult to explain these deterioration and recovery patterns using the routine theories such as mass transfer or the effect by *OLR* [16].

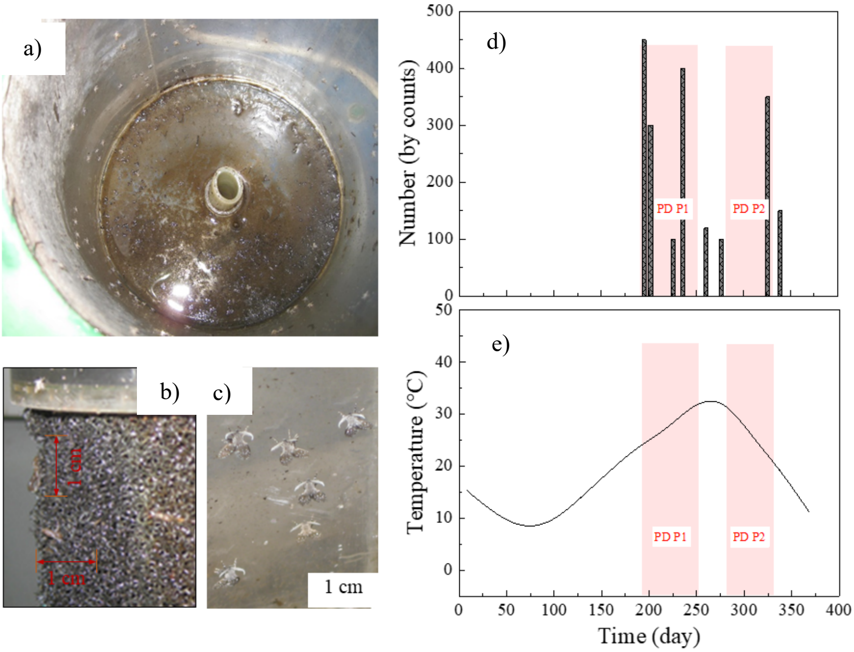

Fig. 4. Relationships between the TBF performance deterioration and the flies:
a) inner side of the closed chamber after dismantling on day 339, b) larva of the *Psychodinae*, c) adult flies appearing in the TBF, d) counts of the flies number, e) ambient temperature curve during the whole operation period with the fitting method of B-spline polynomial least square

Another interesting phenomenon observed on day 180 was that several small flies were found alive in the sealed chamber of the TBF after visual inspection through the transparent plexiglas pipe. The flies could reproduce and freely move in the sealed chamber and were attached on the inner walls of the chamber and on the outer surface of the tubular media. The fly number was counted at different operation stages. Photos of the inner side of the closed chamber with the flies after dismantling on day 339 revealed that very few biofilms accumulated and the flies predated on the biofilms. The number of the flies was large under 20–30 °C of ambient temperature (fitted with B-spline polynomial least square method), as shown in Fig. 4.

At the end of the startup stage (day 60), a thin layer of yellow-brown biofilm accumulated in the filter media and attached to the internal wall of the transparent pipe. When the chamber was opened on day 339, biomass appeared at the bottom and the internal wall of the chamber (Fig. 4a) was much lesser than that in previous studies done for toluene removal by the same type of TBF [17]. Moreover, no biomass was apparently observed on the surface of the tubular filter media (Fig. 4b). Biomass is most important for biofilters, which could directly determine their performance in terms of biomass accumulation rate and its activity [1]. During both PD-P1 and PD-P2, the TBF was operated with small amounts of accumulated biomass in the filter media (Figs. 4a and 4b). The overgrowth of microorganisms can induce excessive biomass accumulation in the filter media, which contributed to the deterioration of biofilters after a long period of operation [10]. However, in the TBF, too little biomass accumulation led to a decrease and fluctuation of the *RE* (PD-P1 and PD-P2) when other operation conditions remained unchanged (Fig. 3). Although TBF recovered to its previous state after these two PD periods, the high biofilter performance mostly relied on the support of high microbial activity of the biomass, which could be greatly impacted by other factors such as shock loadings [1] and even continuously reduced biomass accumulation. Generally, the amount of biomass accumulated in the tubular filter media directly determined the deterioration of TBF performance and its recovery.

Similar to tiny moths, the adventitious flies shown in Fig. 4c were yellowish-grayish in color with short and hairy bodies. The adult flies were 0.2–0.6 cm long and had two wings with tiny white spots in the back and two long antennae in the head. Meanwhile, some larvae at the bottom of the chamber were also found (Fig. 4b). With a narrow head and a narrow terminal segment, the larvae were 0.6–1.2 cm long and 0.1–0.4 cm wide. By appearance identification, the flies in the TBF were the moth fly *Psychodinae*, which often infest sewage networks and municipal wastewater treatment plants. Notably, they have suddenly appeared in public washrooms and house bathrooms in Changsha city. The *Psychodinae* larvae feed on algae, fungi, and bacteria in sewage and organic sludge, and adults feed in polluted water and on flower nectar [27]. In the TBF, both the flies and the larvae were in favor of the organic-rich and damp environment as the biomass accumulation in the chamber. Based on the evidence of morphology and their potential habits, we identified the flies as the moth fly *Psychodinae* from the family Psychodidae [27].

Although the pupae and eggs of the flies were hardly recognizable in the chamber as they were mixed with the biomass, both the adult and larva that appeared in the TBF supported the previous observations of this study that the decreased biofilms were resulted by biological predation. In fact, under an ambient temperature of 20 °C, *Psychodinae* egg hatched within 32–48 h after being laid, and subsequently pupated after 9–15 days, developing into a pupa stage within the next 20–40 h. The cycle from the egg to the adult was about 7–28 days, which could survive for two weeks.

Obviously, the TBF was almost invaded by *Psychodinae* via sludge seeding and nutrient (prepared with tap water) feeding. *Psychodinae* females commonly lay irregular masses of 30–200 eggs in the organic gelatinous film lining the drains, which were easily mixed in water and sludge. Although the bioreactor was never opened at any point in the operation, eggs, pupae, and larva of *Psychodinae* could thrive in the chamber by nutrient addition and mixing with seeding sludge. When the amount of biomass was abundant and the operation condition suitable (middle temperature, moist, etc.), the TBF could be easily infested with *Psychodinae*. Meanwhile, the larva of *Psychodinae* can go half-through the open pore (size of 0.1 cm) of the sponge media, which could lead to over predation of the biomass and even that of the accumulated filter media. Overall, the TBF performance was greatly associated with the number of *Psychodinae*.

Since the larva was difficult to separate in the TBF, the active adult *Psychodinae* was counted for estimating its relative abundance. As shown in Fig. 4d, the number of flies varied significantly with time in the TBF chamber. During the two PD periods, the flies were over 300 on day 195, day 202, day 236 and day 328 but less than 150 on day 261, day 277 and day 339. The TBF performance was directly affected by the number of flies.

The curve of ambient temperature is shown in Fig. 4e. It was apparent that the ambient temperature dramatically fluctuated with time. Both PD periods appeared at middle ambient temperature (Figs. 3d and 4e), during which the TBF became heavily infested with flies. Not only biofilters tend to be operated at middle temperatures for high biomass growth rates and degradation [3, 17], but also it is also optimal for the growth of *Psychodinae* [27]. The infested flies could lead to overconsumption of accumulated biomass especially on the surface of the tubular filter media, which was greatly higher than the biomass growth rate in the TBF. Meanwhile, the *Psychodinae* reproduction could be restricted by limiting the food from accumulated biomass and setting the TBF to ambient temperature. Once the number of flies declined to a lower level, biomass also started accumulating in the filter media, resulting in the recovery of the TBF. However, further studies should be carried out to include in the operational mechanism the dynamics of *Psychodinae,* and biomass accumulation in the TBF, and how they affect each other.

3.4. ELIMINATION CAPACITIES AT VARIOUS ORGANIC LOADING RATES

The variation of *EC* with *OLR* for isobutanol removal by the TBF is shown in Fig. 5, and the average *EC*s at typical *OLR*s (apart from the startup stage and PD periods) are listed in Table 2. As shown in Fig. 5, the *EC* increased with inlet *OLR*, which was similar to previous reports [21]. Except for the startup stage and PD periods, the *EC* was approximately equivalent to the *OLR* under low load conditions, at which the *RE* was closely calculated to be 100%. The critical *EC* at which the overall load will exceed the overall *EC* is ca. 50 g·m^{-3}·h^{-1}.

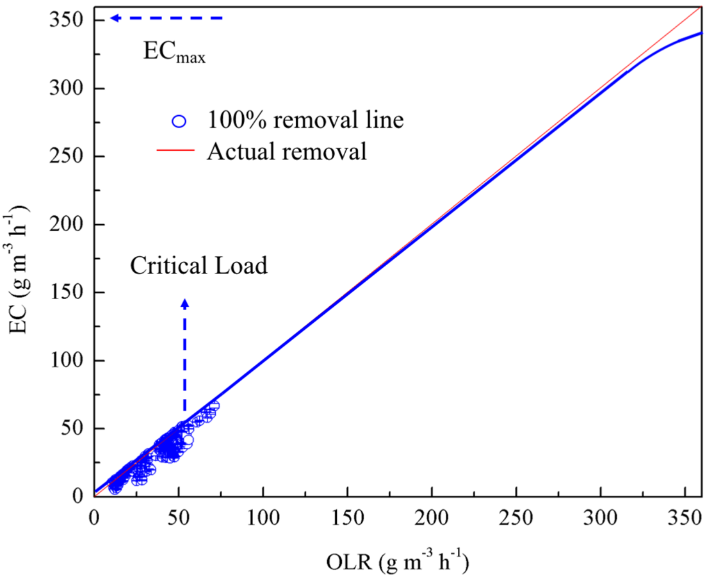

Fig. 5. Variations of elimination capacity (*EC*) with the *OLR*

Table 2

Average *EC*s at typical organic loading rates

OLR [g·m^{-3}·h^{-1}]	*η* [%]	*EC* [g·m^{-3}·h^{-1}]
12.14±0.70	99.39±0.25	12.07±0.71
16.62±0.97	97.69±1.23	16.24±1.11
20.67±1.86	99.58±0.12	20.59±1.87
21.03±1.05	99.34±0.24	20.89±1.09
21.54±0.43	99.69±0.01	21.49±0.43
30.93±8.93	96.33±2.61	29.68±5.85
47.94±6.15	95.10±3.68	45.71±6.35
50.64±4.99	94.14±3.75	47.65±4.80
66.45±4.75	90.89±2.99	60.42±6.35

The maximum *EC* of isobutanol was higher than 70 g·m^{-3}·h^{-1}, and even greater than 350 g·m^{-3}·h^{-1} based on a likelihood analysis with the same isobutanol removal using conventional biofilter [21, 22]. In comparison, *EC* was only 34.8 $g \cdot m^{-3} \cdot h^{-1}$ and 20.9 $g \cdot m^{-3} \cdot h^{-1}$ [22, 23] in the composite bead air biofilter, suggesting that the maximum *EC* for isobutanol removal by the TBF was significantly higher.

The average *EC* was close to *OLR* under lower *OLR*s (below 50 $g \cdot m^{-3} \cdot h^{-1}$) except for 16.62±0.97 $g \cdot m^{-3} \cdot h^{-1}$ (run II-1, Table 2). Apparently, the deviation of the *EC* from the *OLR* further increased with increasing *OLR*. Compared with the toluene removal from waste gases by the TBF [17], the *EC* of isobutanol was slightly higher in this study. The average *RE* was higher than 90% with *OLR*s ranging from 12.14 to 66.45 $g \cdot m^{-3} \cdot h^{-1}$. Even under a low gas *EBRT* of 15 s, the preferable *RE*s and *RE*s under middle or low *OLR*s were still obtained by the TBF. Therefore, the TBF was suitable for treating waste gases with middle or low isobutanol concentration that could maintain a high and stable *RE* even at fluctuating inlet concentrations.

4. CONCLUSIONS

A tubular biofilter (TBF) was successfully used for isobutanol removal from waste gas streams. Within 60 days, the TBF successfully started up even under changing organic loading rate (*OLR*) from 31.3 to 15.6 $g \cdot m^{-3} \cdot h^{-1}$. The average removal efficiency was higher than 90% when the *OLR* varied from 12.14 to 66.45 $g \cdot m^{-3} \cdot h^{-1}$ under normal operating conditions. The elimination capacity (*EC*) was 60.42 $g \cdot m^{-3} \cdot h^{-1}$ at the inlet *OLR* of 66.45 $g \cdot m^{-3} \cdot h^{-1}$, with the critical *EC* being around 50 $g \cdot m^{-3} \cdot h^{-1}$. Two distinct performance deterioration periods were observed during days 186–253 and days 280–334, and both of which recovered through the TBF. During these periods, the larvae and adult moth flies identified as *Psychodinae* were observed in the chamber, which could greatly affect the TBF performance.

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