0273-2289/00/84–86/0469/$12.50

Design and Performance of a Fibrous Bed Bioreactor for Odor Treatment

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Abstract

Biological processes have become popular for odor treatment. In this study, a novel fibrous bed bioreactor was applied for treatment of odorous gas. The column reactor was packed with spirally wound fibrous sheet material on which a consortium of microorganisms selected from activated sludge was immobilized. The first stage of this work comprised a preliminary study that aimed at investigating the feasibility of the fibrous bed bioreactor for treatment of odorous volatile fatty acids (VFAs). In this stage, the performance of a fibrous bed bioreactor at increasing mass loadings ranging from 9.7 to 104.2 g/(m^3·h) was studied. VFA removal efficiencies above 90% were achieved at mass loadings up to 50.3 g/(m^3·h). At a mass loading of 104.2 g/(m^3·h), removal efficiency was found to be 87.7%. In the second stage of the work, the process was scaled up with design and operational considerations, namely, packing medium, process condition, and configuration selections. A trickling biofilter with synthetic fibrous packing medium was selected. It was operated under countercurrent flow of gas and liquid streams. The effects of inlet concentration and empty bed retention time on bioreactor performance were studied. The bioreactor was effective in treating odorous VFAs at mass loadings up to 32 g/(m^3·h), at which VFAs started to accumulate in the recirculation liquid, indicating that the biofilm was unable to degrade all the VFAs introduced. Although VFAs accumulated in the liquid phase, the removal efficiency remained above 99%, implying that the biochemical reaction rate, rather than gas-to-liquid mass transfer rate, was the limiting factor of this process. The bioreactor was stable for long-term operation; no clogging and degeneration of the packing medium was observed during the 4-mo operation.

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Index Entries: Fibrous bed bioreactor; odor treatment; volatile fatty acids; trickling biofilter.

Introduction

Odorous gases are emitted in the waste gas stream from such industries as chemical production *(1,2)*, municipal sewage treatment *(3)*, bioprocesses *(4)*, and food processing *(2)*. For humans, the detectability of and tolerance limit for the odorous components in air are often at very low concentrations (parts per million or even parts per billion levels). As a consequence, small emissions of malodorous compound often result in odor nuisance, which has often led to a significant number of complaints to those responsible for generating the odors and to the relevant authorities. The number of complaints has been increasing in recent decades, mainly because of the public's growing environmental consciousness and realization of its rights to have a cleaner environment *(2)*.

In countries such as the Netherlands, Singapore, Japan, Australia, England, Canada, and the United States, to reduce odor pollution problems, statutory control has been established to restrict the emission of odorous or toxic compounds into the environment. To meet the emission standards required by regulations, various odor treatment technologies have been developed and applied. Among these are physicochemical methods, i.e., masking, activated carbon adsorption, catalytic thermal oxidation, ozonation, wet chemical scrubbing, and biological methods. Recently, biological abatement technologies have increased in popularity because of low operational and maintenance costs, good stability and reliability, operational simplicity, minimal requirements for energy and raw materials, and minimal secondary waste production *(2,5,6)*.

Biofiltration is the most common biological odor treatment method. Waste gases are passed through a biologically active porous medium using soil, peat, activated carbon, bark, and leaves as basic filter material, and are biodegraded by indigenous microbes. Biofiltration has been applied on a full scale for control of odorous emissions from many industries. Fouhy *(1)* has listed the compounds that have been treated by biofilters together with their sources, and Leson and Winer *(7)* have presented a list of successful biofilter applications in Europe.

Although high-efficiency odor removal can be achieved with conventional biofilters, soil and compost as the biological attachment media have several drawbacks owing to their low porosity and high compactness, causing high resistance and channeling flow. These biofilters are also subject to clogging and dehumidification over long-term operation *(2,7)*. Moreover, control of reaction in the biofilter is difficult *(8,9)*. Furthermore, the large footprint of conventional biofilters limits their use in small and crowded city areas.

In recent years, a new type of biofilter that can overcome the aforementioned disadvantages has been developed for various bioprocessing purposes *(10–13)*. The bioreactor contains a packed bed of spiral-wound porous

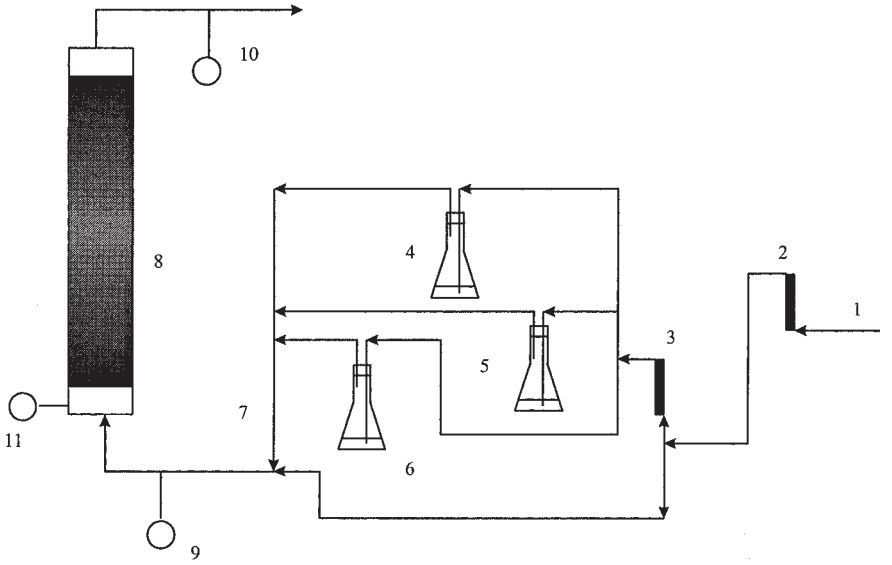

Fig. 1. Experimental apparatus of the feasibility study. 1, Compressed air; 2, flowmeter controlling the total gas flow rate; 3, flowmeter controlling VFA concentration; 4–6, VFA solution; 7, VFA-contaminated gas; 8, fibrous bed bioreactor; 9–11, sampling ports: gas inlet, gas outlet, and liquid inside reactor, respectively.

fibrous sheet materials with built-in vertical spaces or interstices between adjacent fibrous sheets to allow gas to flow upward relatively freely through the packed bed. The fibrous bed with high porosity (>90%) and high surface area provides good multiphase contacts and an ideal environment in which microbial growth and biochemical reactions can take place. In environmental applications, the fibrous bed bioreactor has been studied for applications in the treatment of BTEX-contaminated groundwater and waste streams *(14)*.

The objective of this study was to develop a novel fibrous bed bioreactor to treat odorous pollutants present in contaminated air streams from the various industries. The work was carried out in two stages: first, to study the feasibility of the fibrous bed bioreactor for odor treatment and, second, to design the odor treatment operation and obtain reliable operational information on the bioreactor performance under realistic operational conditions. Hence, the effects of inlet odorant concentration and gas empty bed retention time (EBRT) on removal efficiency were studied.

Materials and Methods

Feasibility Study

Bioreactor System

The bioreactor system (Fig. 1) consisted of a cylindrical glass column with an id of 5 cm and a height of 73 cm. A 52 × 30 cm cotton fabric packing

material was spirally wound together with a stainless steel wire cloth of the same dimensions. The empty bed volume was 1 L with a porosity of 90%.

The simulated odor gas was generated by bubbling air through 25% (v/v) volatile fatty acid (VFA) solutions (acetic, propionic, and butyric acids). The odorous gas was introduced at the bottom of the reactor and treated gas was exited from the top.

The fibrous bed packing was operated as a submerged biofilter. Gaseous samples were taken from the inlet and outlet of the fibrous bed bioreactor, and liquid samples were at the bottom of the column reactor.

Bioreactor Start-Up and Operation Conditions

Activated sludge was used as the seed culture for this study. The VFA-degrading microbes were selected by growing in a medium containing 20 g/L of VFA (acetic, propionic, and butyric acids, 6.67 g/L each) using a stirred-tank reactor with a 4 L working volume. The harvested cell broth was recirculated between the column reactor and the stirred tank for cell immobilization. After the microbes were immobilized on the fibrous packing medium, gaseous VFA of mass loadings ranging from 9.7 to 104.2 g/(m^3·h) was introduced into the bioreactor.

Process Operation Study

Bioreactor System

The bioreactor system was similar to the one used in the feasibility study (Fig. 2). The reactor system consisted of a cylindrical acrylic column with an id of 37 mm and a height of 120 cm. A 60 × 70 cm fibrous packing material was spirally wound together with a stainless steel wire cloth of the same dimensions. The empty bed volume was 3 L with a porosity of 95%.

The simulated odorous VFA gas was generated by bubbling air through a 10% (v/v) VFA solution (butyric and valeric acids). Different airflow rates were used to vary the inlet VFA concentrations.

The bioreactor was operated as a trickling biofilter, under countercurrent flow of gas and liquid streams. The odorous gas was introduced at the bottom and treated gas was exited from the top of the reactor. The recirculation liquid was trickled on top of the fibrous bed at 200 mL/min and exited from the bottom and returned to the recirculation tank. The recirculation liquid provided moisture, as well as inorganic nutrients including $(NH_4)_2SO_4$, KH_2PO_4, and $MgSO_4$, to the microorganisms in the fibrous bed. The recirculation tank also served as a sedimentation tank from which excess biomass from the bioreactor was removed. Gas sampling ports were located at the inlet and outlet of the reactor. Liquid sampling ports were at the bottom of column and at the recirculation tank.

Bioreactor Start-Up and Operation Conditions

The bioreactor start-up procedure was similar to that of the feasibility study, except valeric acid was used in place of acetic and propionic acids,

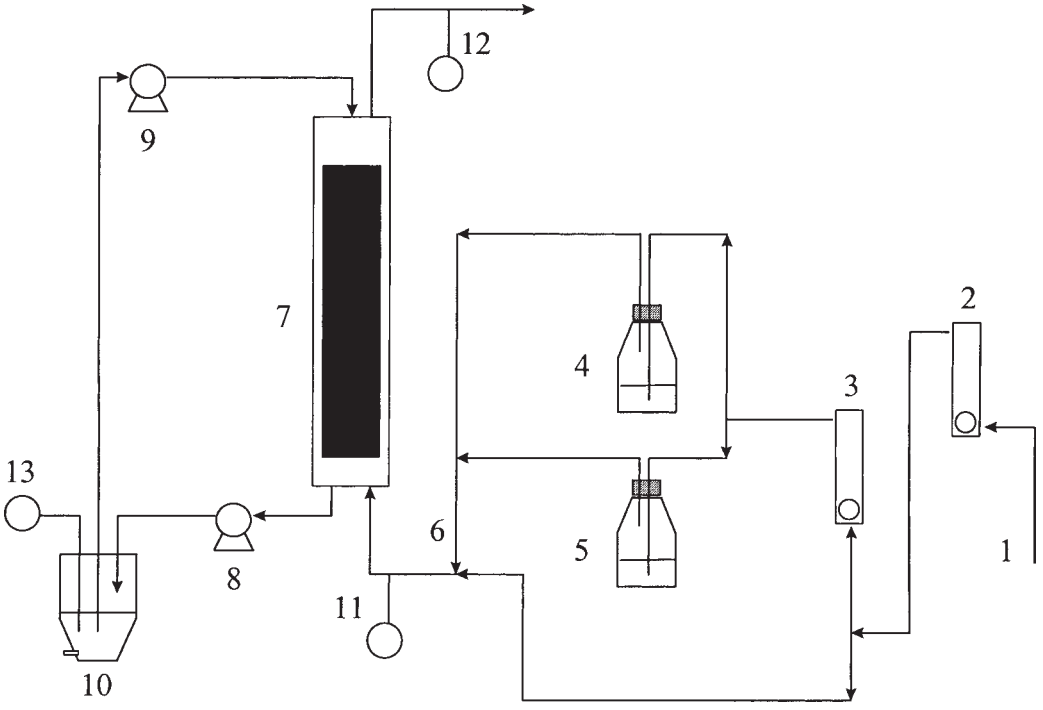

Fig. 2. Bioreactor system in process operation study. 1, Compressed air; 2, flowmeter controlling the total gas flow rate; 3, flowmeter controlling VFA concentration; 4 and 5, VFA solution; 6, VFA-contaminated gas; 7, fibrous bed bioreactor; 8 and 9, recirculation pumps; 10, recirculation tank; 11–13, sampling ports: gas inlet, gas outlet, and recirculation tank, respectively.

and the concentration of each acid used was 10 g/L. After the start-up period, the odorous gas was supplied to the bioreactor at flow rates ranging from 2 to 6 L/min (EBRT 30–90 s) and with inlet VFA concentrations ranging from 0.08 to 0.86 g/m^3.

Analytical Methods

The inlet and outlet VFA concentrations were determined using an HP 5890 gas chromatographic system equipped with an HP-FFAP column and a flame ionization detector. Nitrogen was used as the carrier gas at 20 mL/min. The temperature of the injector and detector was 280 and 300°C, respectively. The oven temperature profile was controlled from 80 to 200°C at 20°C/min.

The VFA concentration in the liquid phase was determined according to Levett *(15)*. The liquid samples were first centrifuged at 12,000 rpm for 5 min. Thereafter, the cell-free samples were acidified by 50% aqueous H_2SO_4 and then mixed with diethyl ether. One microliter of the ether layer was injected into the gas chromatograph.

Table 1
Bioreactor Performance Under Increasing Mass Loadings

Mass loading (g/[m³·h])	Removal efficiency (%)	VFA concentration in liquid phase (g/L)
5.1	95.8	—
9.7	98.6	—
12.4	96.2	—
20.6	96.5	—
22.4	95.2	1.0
50.3	91.5	5.5
104.2	87.8	6.7

Results and Discussion

Feasibility Study

Table 1 presents the effect of mass loading on bioreactor performance. At VFA mass loadings below 22.4 g/(m³·h), the VFA concentration from the gas outlet and in the liquid inside the bioreactor was always nondetectable (the detection limit was 100 μg/L), and a steady pH in the liquid phase was observed. Under this condition, there was no accumulation of VFA inside the bioreactor indicating that the microorganisms were able to degrade all the VFA introduced.

When total mass loading was increased to 22.4 g/(m³·h), VFAs were still nondetectable in the gas outlet. However, VFAs started to accumulate in the liquid phase (Table 1). When total VFA mass loading was raised to 50.3 g/(m³·h), the outlet VFA concentration was detectable, the removal efficiency was reduced to 91.9%, and the resulting removal capacity was 46.1 g/(m³·h). The total VFA mass loading was further increased to 104.2 g/(m³·h), the total VFA removal efficiency was lowered to 87.8%, and the total VFA concentration in the liquid phase was 6.7 g/L, with 0.5 g/L of acetic, 3.1 g/L of propionic, and 3.1 g/L of butyric acid, respectively.

Throughout the course of the bioreactor operation, although the accumulation of VFA in the liquid phase did not show an adverse effect on removal efficiency, it was undesirable because the presence of VFA led to a decrease in the pH of the liquor in the system, which, in turn, adversely affected the biodegradation process. In addition, instead of removing odor, an offensive odor was generated from the outlet gas even at a very low VFA concentration in the recirculation liquid. Thus, the optimum operating condition of this process should be zero accumulation of VFA in the liquid phase.

The results revealed that the application of a fibrous bed bioreactor for odor treatment was feasible. However, two serious problems were observed. First, the packing medium was clogged by the microbial inhabitants. This was owing to the submerged bed configuration, which did not allow for disposal of excess biomass, thereby resulting in the clogging and

Table 2
Bioreactor Operational Performance
Under Increasing VFA Concentrations at Different EBRTs

EBRT (s)	VFA concentration (g/m^3)	Mass loading ($g/[m^3 \cdot h]$)	Removal efficiency (%)	VFA accumulation in recirculation liquid
90	0.12	4.8	99.5	–
	0.31	12.4	99.5	–
	0.54	21.6	99.8	–
	0.86	34.4	99.6	+
60	0.09	5.4	99.4	–
	0.28	16.8	99.4	–
	0.45	27.0	99.6	–
	0.62	37.2	99.7	+
45	0.08	7.2	99.9	–
	0.19	17.1	99.1	–
	0.42	37.8	99.6	+
30	0.05	6.0	99.2	–
	0.14	16.8	99.6	–
	0.31	37.2	99.1	+

plugging of the filter medium. Second, the fibrous packing was found to be degraded during the study, indicating that cotton was a biodegradable material and unsuitable for long-term processes.

Process Operation Study

In this stage of the study, to optimize the process, it was scaled up with design and operation considerations. The problems found in the feasibility test are likely to be solved by using synthetic fiber as packing medium instead of cotton. In addition, a trickling biofilter configuration was employed, which allows elimination of excess biomass. To obtain reliable information on the bioreactor performance under realistic operational conditions, the reactor performance under different loading conditions was studied.

Effect of Inlet VFA Concentration

The effect of inlet VFA concentration on bioreactor performance was studied by increasing the gaseous VFA concentrations at fixed EBRTs of 90, 60, 45, and 30 s. As shown in Table 2, at an EBRT of 90 s, a high removal efficiency of 99.5% was obtained. When the inlet concentration was increased to 0.86 g/m^3, the bioreactor responded with an accumulation of VFA in the recirculation liquid instead of an increased VFA concentration in the outlet gas, and the removal efficiency remained higher than 99%.

At a shorter EBRT of 60 s, VFA was found to be accumulating at a lower inlet concentration of 0.62 g/m^3. Similar results were obtained at shorter EBRTs of 45 and 30 s. The accumulation of VFA in the recirculation liquid was found at inlet concentrations of 0.42 and 0.31 g/m^3, respectively.

Table 3
Bioreactor Operational Performance
Under Decreasing EBRTs at Different VFA Concentrations

VFA concentration (g/m^3)	EBRT (s)	Mass loading ($g/[m^3 \cdot h]$)	Removal efficiency (%)	VFA accumulation in recirculation liquid
0.08	90	3.2	99.5	–
	60	4.8	99.5	–
	45	6.4	99.8	–
	30	9.6	99.6	–
0.2	90	8	99.4	–
	60	12	99.4	–
	45	16	99.6	–
	30	24	99.7	–
0.4	90	16	99.9	–
	60	24	99.1	–
	45	32	99.6	+
	30	48	99.2	+
0.7	90	28	99.6	–
	60	42	99.0	+
	45	56	99.2	+

The accumulation of VFA compounds in the liquid phase indicated that the biofilm was unable to degrade all the VFA introduced. Among the EBRTs studied, VFA began to accumulate at similar mass loadings between 34.4 and 37.8 $g/(m^3 \cdot h)$.

Effect of EBRT

The effect of gas retention time on bioreactor performance was investigated by shortening the EBRT, and the inlet VFA concentrations were set at 0.08, 0.2, 0.4, and 0.7 g/m^3. As shown in Table 3, at low inlet concentrations of 0.08 and 0.2 g/m^3, removal efficiencies of higher than 99% were obtained, and no VFA accumulation was found in the liquid phase, even when the reactor was operated at a short EBRT of 30 s.

When the inlet concentration was set at 0.4 g/m^3, accumulation of VFA started to show when EBRT was 45 s. When the VFA concentration was further increased to 0.7 g/m^3, VFA started to show when EBRT was 60 s, indicating that a longer retention time was needed for complete degradation as the concentration was increased. At mass loadings of 32 and 42 $g/(m^3 \cdot h)$, VFA started to show in the liquid phase (Table 3).

The results reveal that bioreactor performance was mainly affected by mass loading, whereas the inlet concentration or EBRT alone could not affect bioreactor performance. It was observed that VFA started to accumulate in the recirculation liquid at a mass loading of 32 $g/(m^3 \cdot h)$, which was regarded as the critical mass loading. Nevertheless, the removal efficiencies remained higher than 99%. This finding implied that the mass transfer

of VFA compounds from gaseous to liquid phase was not the rate-determining step in the process and that the VFA removal rate was mainly limited by the biochemical degradation in the biofilm.

Long-Term Stability of the Bioreactor

During the 4-mo period of operation, no clogging or aging problems of the packing medium were encountered. This long-term stability of the fibrous bed bioreactor was attributed to its highly porous fibrous matrix and spirally wound packing configuration, which resulted in an ideal hydrodynamic environment and efficient mass transfer that had prevented the formation of a cluster of biomass. In addition, the microbial cells in the fibrous bed were constantly being renewed with news cells, thus avoiding problems such as aging and sloughing of biofilm commonly seen in conventional biofilters.

Conclusion

In the feasibility study, the fibrous bed bioreactor was successfully applied as a submerged biofilter to treat odorous VFA. At a mass loading 104.2 g/(m^3·h), the overall removal efficiency was 87.7%. For VFA mass loading below 50.3 g/(m^3·h), a removal efficiency higher than 90% was attained. However, this submerged-bed configuration with cotton fibrous packing was unsuitable for long-term processes because of problems with clogging and degeneration of the packing medium.

In the process operation study, the trickling bioreactor with synthetic fibrous packing was shown to be effective in removing odorous VFAs from fouled gas streams. The performance of the process was affected by mass loading, but not by inlet concentration or EBRT alone. The critical mass loading was found to be 32 g/(m^3·h), at which VFAs started to accumulate in the liquid phase. Removal efficiencies of higher than 99% were still obtained, which indicated that the biodegradation process was limited by microbial activity. The bioreactor also showed long-term stability, indicating good potential for industrial scale-up.

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