COMPARISON OF AUTOTROPHIC AND MIXOTROPHIC BIOFILTERS FOR H_2S REMOVAL

By Ying-Chien Chung,[1] Chihpin Huang,[2] Jill Ruhsing Pan,[3] and Ching-Ping Tseng[4]

ABSTRACT: We demonstrate that the facultative chemoautotroph *Thiobacillus novellus* CH 3 removes hydrogen sulfide (H_2S) gas in continuous reactors under nutrient-limiting conditions. Extensive tests including removal characteristics, metabolic products, and removal efficiencies of H_2S by *T. novellus* CH 3 were conducted in autotrophic and mixotrophic environments. The optimal pH value and temperature required to remove hydrogen sulfide are found to be pH 7 and 26°C. The biofilter had an H_2S removal efficiency greater than 99.5% under the mixotrophic condition after 10-day operation. The results show that the maximum removal rate and saturation constant were 1.9 g S/d per kg bead and 69.2 ppm, respectively. The main metabolic product of H_2S oxidation was determined to be sulfate, but the conversion ratio was dependent on the growth environment. These results suggest that the mixotrophic potential of *T. novellus* CH 3 biofilter provides a significant advantage in H_2S removal over autotrophic biofilters.

INTRODUCTION

Hydrogen sulfide (H_2S) is a colorless and corrosive air pollutant that is extremely toxic (Roth 1993). It occurs widely in nature and is released by industrial processes, such as petrochemical refining, wastewater treatment, food preparation, paper and pulp manufacturing, and in the treatment of fuels (Eikum and Storhang 1986; Yang and Allen 1994). Excess H_2S must be removed for reasons of health and safety, because it has a great potential to irritate eyes and injure the human central nervous system (Vanhoorne et al. 1995). Conventional treatment of waste gases, wastewater, and ground water containing H_2S use some common technologies. These technologies include activated carbon adsorption, ozone oxidation, incineration, air stripping, and microfiltration (Eby and Wilson 1969; Barth et al. 1984; Mannebeck 1986; Thompson et al. 1995). However, conventional treatment and disposal costs are high and secondary-pollutant issues may arise. The continuing demand for improved process economy and efficiency has led to investigations into microbiological alternatives to conventionally physical/chemical methods (Bohn 1992). Biofilters decontaminate waste gas by passing it through a damp medium that supports a vigorous culture of microorganisms. The biofiltration process can serve as a most effective means when applied to dilute, easily biodegradable waste gases under appropriate sets of conditions (Leson and Winer 1991). Thus, H_2S is an excellent candidate for removal by biofiltration.

A wide range of biofilter bed materials as carriers have been studied (Rands et al. 1981; Lee and Shoda 1989; Leson and Winer 1991). Originally, biofilters are developed with soils as carriers; however, soils are limited in effectiveness because they are prone to short-circuiting and clogging (Carlson and Leisner 1966). Compost is inexpensive and purifies waste gases well, but it suffers from aging effects that create short-circuiting of the biofilter and further decrease the effectiveness of the biofilter (Langenhove et al. 1992). Activated carbons also perform well in removing waste gases, but they are too expensive to justify the efficiency difference (Medina et al. 1995). Fibrous peat, used as a packing material, has been shown to perform better than soil, compost, or activated carbon (Leson and Winer 1991); however, a larger space is required when a biofilter packed with microorganism-laden peat is used to treat large quantities of hydrogen sulfide at low concentrations (<20 ppm) (Tanji et al. 1989). Ca-alginate beads have advantages as a biofilter medium in comparison with other commonly used biofilters. Recent work has shown that Ca-alginate beads can have a high microorganism content and prevent microorganism losses (Kokufuta et al. 1982).

The presence of microorganisms is necessary for effective removal of H_2S gas. Although activated sludges (mixed culture) have been used in operating biofilters, acclimation times of at least 1–3 weeks are required (Ottengraf and Van Den Oever 1983). Recently, the use of pure cultures is gaining a lot of attention because it shortens start-up time and enhances removal efficiencies and capacities. Both autotrophic and heterotrophic microorganisms have been employed in pure culture studies, and there are inherent differences in their nutritional requirements and abilities to catalyze specific reactions. Some autotrophic bacteria, such as members of the *Thiobacillus* species have been seeded into bioreactors and used to metabolize H_2S. The products of H_2S oxidation are dependent on the strain of *Thiobacillus sp.* employed (Sublette and Sylvester 1987; Cho et al. 1991a; Chung et al. 1996a). Among heterotrophic bacteria, only *Xanthomonas sp.* and *Pseudomonas putida* have been reported to oxidize H_2S in biofilter systems (Cho et al. 1991b; Chung et al. 1996b). Autotrophic biofilters have shown high affinity for H_2S, but failed to remove reliably low concentrations of H_2S through sustained experiments. However, heterotrophic biofilters have shown opposite tendencies (Huang et al. 1996). Moreover, facultative chemoautotrophs such as *Thiobacillus novellus* possess the unique potential for autotrophic as well as heterotrophic growth. Hence, these bacteria are apparently adaptable to different environments, i.e., autotrophic, heterotrophic, or mixotrophic conditions (Matin 1978). Studies have shown adaptive physiologic/metabolic response of *T. novellus* to mixotrophic environments (Leefeldt and Matin 1980; Perez and Matin 1980), but little engineering information, such as desired control mechanisms, and proper design and maintenance of biofilters for H_2S removal is available.

In this study, we used Ca-alginate to immobilize *T. novellus* CH 3 and studied an H_2S-fed biofilter operated under autotrophic and mixotrophic conditions.

[1]PhD, Nat. Sci. Council, Taipei, Taiwan, R.O.C.; formerly, Inst. of Envir. Engrg., Nat. Chiao Tung Univ., Hsinchu, Taiwan, R.O.C. 30039.

[2]Prof., Inst. of Envir. Engrg., Nat. Chiao Tung Univ., Hsinchu, Taiwan, R.O.C. 30039. Correspondence should be addressed to Chihpin Huang.

[3]Res., Inst. of Envir. Engrg., Nat. Chiao Tung Univ., Hsinchu, Taiwan, R.O.C. 30039.

[4]Assoc. Prof., Inst. of Biol. Sci. and Technol., Nat. Chiao Tung Univ., Hsinchu, Taiwan, R.O.C. 30039.

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MATERIALS AND METHODS

Organism Cultivation and Buffer Preparation

The bacteria used in this study were isolated from piggery wastewater. The wastewater was mixed with a pH 7 mineral salts medium containing KH_2PO_4, 2 g/L; K_2HPO_4, 2 g/L; NH_4Cl, 0.6 g/L; $MgCl_2 \cdot 6H_2O$, 0.3 g/L; and $FeSO_4 \cdot 7H_2O$, 0.02 g/L. As the only source of energy, hydrogen sulfide generated by feeding solution of Na_2S and HCl was supplied from 5 to 150 ppm into the Erlenmeyer flasks. Erlenmeyer flasks were closed with rubber stoppers containing inlet and outlet pores and the inlet and outlet gas concentrations were measured regularly. When the outlet gas concentration was nearly zero, the inlet gas concentration was increased to a desired higher level. This process was repeated until a constant level of outlet gas concentration was detectable. At this stage, the process of acclimating microbes was assumed to be completed. One milliliter of bacterial solution was transferred repeatedly to fresh solid medium by spread plate method. The dominant colonies were reserved and further purified until appearance of single colony. The isolated strain was identified as *T. novellus* by the Food Industry Research and Development Institute in Taiwan. During continuous-treatment experiments, the autotrophic inflow medium included KH_2PO_4, 1.2 g/L; K_2HPO_4, 1.2 g/L; NH_4Cl, 0.4 g/L; $MgCl_2 \cdot 6H_2O$, 0.2 g/L; and $FeSO_4 \cdot 7H_2O$, 0.01 g/L. The mixotrophic inflow medium was obtained by supplementing the autotrophic inflow medium with 0.2 g glucose. The final pH of the culture was adjusted to 7 using 2 N NaOH or HCl. In batch experiments, for measurement of the pH effect on sulfide removal by *T. novellus* CH 3 under autotrophic and mixotrophic conditions, the *T. novellus* CH 3 were suspended in phosphate buffers in the pH range of 5.5–8.0 at 30°C. The removal rates were measured at sulfide concentrations between 0 and 10 mM. For each pH value, the values of the saturation constant K_s and the maximum removal rate V_m were calculated using Michaelis-Menten equation via the linear regression method.

Preparation of Immobilized Cells

T. novellus CH 3, grown in 100-mL nutrient broth, was harvested by centrifugation (7,500 × *g* for 10 min). The organisms were washed three times with sterile distilled water, followed by immersing in a sterile 4% Na-alginate solution (10^5 cells/mL) and then mixing with a 4% $CaCl_2$ solution. Upon mixing, 3-mm-diameter immobilized beads were formed immediately. These gel beads then were activated by flushing with sterile buffer solution for 5 h. The activated beads exhibited excellent mechanical strength in the continuous experiments.

Apparatus and H_2S Removal for Continuous Operation

A description of the laboratory-scale experimental biofilter was described previously by Chung et al. (1996c). Glass columns (60 mm ϕ × 40 cm of working height) were packed with cell-laden Ca-alginate beads. In each column, 0.5 kg dry beads were packed in a column of 1.44 L. Initial cell numbers in each column were counted to be approximately 10^7 colony-forming units (cfu) per 1 g of dry bead. In the continuous experiment, H_2S gas at different concentrations (10, 20, and 60 ppm) was introduced to the biofilter at a flow rate of 36 or 72 L/h. The $H_2S_{(g)}$ was supplied from a gas cylinder, diluted with compressed air, forced through a filter unit (0.45 μm), and then passed through the humidification bottle into the bottom of biofilter. The effect of temperature on the volumetric oxidation rates and removal efficiencies of the biofilters was studied in the range of 10–30°C controlled by refrigerated circulator circulating water via heat exchanger and while the flow rates were from 18 to 185 L/h. The products from the metabolization of H_2S by *T. novellus* CH 3 also were analyzed during the continuous experiment.

Kinetic Analysis

The H_2S removal rate in the immobilized-cell biofilter was calculated using the following equation derived from the Michaelis-Menten equation (Hirai et al. 1990):

$$\frac{1}{R} = \frac{K_s}{V_m} \times \frac{1}{C_{ln}} + \frac{1}{V_m} \tag{1}$$

where R (g S/d per kg dry bead) = removal rate; C_{ln} (ppm) = logarithmic mean concentration of H_2S at the inlet and outlet of the biofilter; V_m (g S/d per kg dry bead) = maximum removal rate; and K_s (ppm) = half-saturation constant. With the use of the linear relationship between $1/C_{ln}$ and $1/R$, V_m and K_s were calculated from the slope and intercept.

Criteria for Design of Scale-Up Biofilter

The target concentrations of H_2S at the biofilter outlet were presumed as 0.1 and 1 ppm. The maximum inlet concentrations and critical H_2S loads needed to satisfy this effluent concentration (0.1 or 1 ppm) were obtained at various space velocity (SV) according to the following equation (Tiwaree et al. 1992):

$$SV = \frac{\alpha}{(C_0 - C_e)} \times V_m \times \frac{C_{ln}}{(K_s + C_{ln})} \tag{2}$$

where SV (1/d) = F ($1/S_aL$); F = gas flow rate (m^3/d); S_a = column cross section (m^2); L = packing height (m); C_0 = inlet concentration (ppm); C_e = outlet concentration (ppm); and α = conversion coefficient (kg dry bead/g S). Let C_e be 0.1 or 1 ppm in (2), and the maximum C_0 can be estimated at various SVs. The critical loads (g S/d per kg bead) of the biofilters can be obtained using (3)

$$\text{critical load} = \frac{SV \times C_0}{\alpha} \tag{3}$$

Analytical Methods

Inlet and outlet H_2S gas concentrations in the biofilter were measured continuously using a single point monitor (MDA Scientific) in the range of 50–1,500 ppb or periodically measured by gas detector tubes (GASTEC, Tokyo, Japan) in the range of 1–60 ppm. During continuous experiments, the variation of H_2S concentration at steady state was found to be within ±5%. The H_2S outlet concentration was reported as average values from 12 assays. Five grams (wet-weight) of cell-laden beads was dissolved in 95 mL of 0.1 M sodium citrate solution and the sulfur compounds and their amounts in the solution were determined. Sulfate ion concentrations in the solution were measured by ion chromatography (Dionex 4500i). Sulfite was determined by titration using a standard potassium iodide-iodate titrant and a starch indicator [American Public Health Association (APHA) 1992]. Sulfide was determined using an ion-specific electrode (SCHOTT, Germany).

RESULTS AND ANALYSIS

Effect of pH on Sulfide Degradation

At six different pH values ranging from 5.5 to 8, the kinetics of H_2S removal were measured at concentrations between 0 and 10 mM in autotrophic and mixotrophic batch cultures. The pH effects on the sulfide oxidation kinetics of *T. novellus* CH 3 are presented in Table 1. For each pH value, the saturation constant K_s and the maximum removal rate V_m were calculated

TABLE 1. Effect of pH on Saturation Constant and Maximum Removal Rate of *Thiobacillus novellus* CH 3 for Sulfide Degradation in Autotrophic and Mixotrophic Environments at $T = 26°C$

	Autotrophic Environments		Mixotrophic Environments	
pH (1)	K_s (ppm) (2)	V_m (g S/d per kg bead) (3)	K_s (ppm) (4)	V_m (g S/d per kg bead) (5)
5.5	185.6	0.76	152.3	0.89
6	138.3	1.08	111.3	1.26
6.5	86.8	1.79	77.8	1.74
7	84.3	1.85	74.5	1.81
7.5	89.3	1.73	80.4	1.68
8	139.5	1.13	100.5	1.34

from (1) using linear regression. Trends of pH versus K_s profiles indicate that K_s decreases with the increase of pH. The optimal pH value for sulfide removal was 7 regardless of autotrophic or mixotrophic growth conditions. From an operational standpoint, the control of pH is an important parameter in sulfide treatment, and this study suggests the optimal pH value is approximately 7. The saturation constants under mixotrophic conditions were lower than those under autotrophic conditions. Thus, in mixotrophic environments, *T. novellus* CH 3 exhibited higher enzymatic affinity for sulfide than it did in autotrophic environments. Our results are in agreement with previous studies, which have shown that *T. novellus* had higher cell-growth rates and glucose-transport activity in mixotrophic environments than in autotrophic environments (Matin et al. 1980; Perez and Matin 1982).

Effect of Temperature on H_2S Removal

Fig. 1 shows the H_2S oxidation rate of *T. novellus* CH 3 in autotrophic and mixotrophic environments ranging in temperature from 10 to 30°C. When the biofilters were supplied with 60 ppm H_2S at a flow rate of 36 L/h, the H_2S oxidation rate increased with the temperature, reaching its maximum at approximately 26°C. The effect of temperature on H_2S oxidation rate was almost the same whether *T. novellus* CH 3 was in an autotrophic or mixotrophic environment. In general, the relationship between reaction rate and temperature can be approximated using the Arrineus equation

$$K_T = K_{20}\theta^{(T-20)} \tag{4}$$

where K_T = reaction rate at T°C (g S/m^3 per day); K_{20} = reaction rate at 20°C (g S/m^3 per day); θ = temperature-dependency coefficient; and T = temperature (°C). We obtained θ on the basis of experimental results using linear regression analysis from Fig. 1 and the values were

$\theta = 1.023$ under autotrophic conditions

$\theta = 1.025$ under mixotrophic conditions

There was no significant difference in θ between the autotrophic and the mixotrophic biofilter at the temperature between 10 and 26°C.

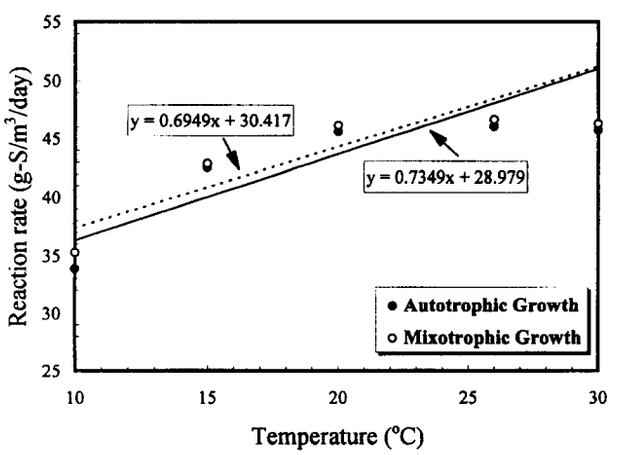

FIG. 1. Effect of Temperature on H_2S Oxidation Rate of *Thiobacillus novellus* CH 3 Biofilters in Autotrophic (Solid Line) and Mixotrophic (Dash Line) Environments

H_2S Removal Rate in Continuous Operation

Fluctuations in inlet H_2S concentrations were examined in the 10–60 ppm range at flow rates of 36 and 72 L/h. The H_2S removal efficiency was calculated from the difference in inlet and outlet concentrations. The H_2S removal efficiencies of the immobilized *T. novellus* CH 3 biofilters in autotrophic and mixotrophic environments at 36 L/h are shown in Figs. 2(a and b), respectively. The variation ranges in the figures were between maximum and minimum removal efficiency for different inlet concentrations. These results demonstrated that the mixotrophic biofilter achieved a steady-state condition (10 days) earlier than did the autotrophic biofilter (13 days). The mixotrophic biofilter showed excellent operational efficiency (>99.5%) regardless of whether the flow rate was 36 or 72 L/h (data not shown). By contrast, a slightly lower H_2S removal efficiency (>98.3%) for the autotrophic biofilter was observed. The higher H_2S removal efficiency achieved by the mixotrophic biofilter appears to be the contribution of enzymatic affinities. The data suggest that the mixotrophic potential of the *T. novellus* CH 3 biofilter could provide significant advantages over the autotrophic biofilter.

Effect of Residence Time on H_2S Removal

The H_2S removal efficiency as a function of residence time at inlet concentration of 60 ppm is shown in Fig. 3. The *T. novellus* CH 3 biofilter achieved a steady-state condition in 72

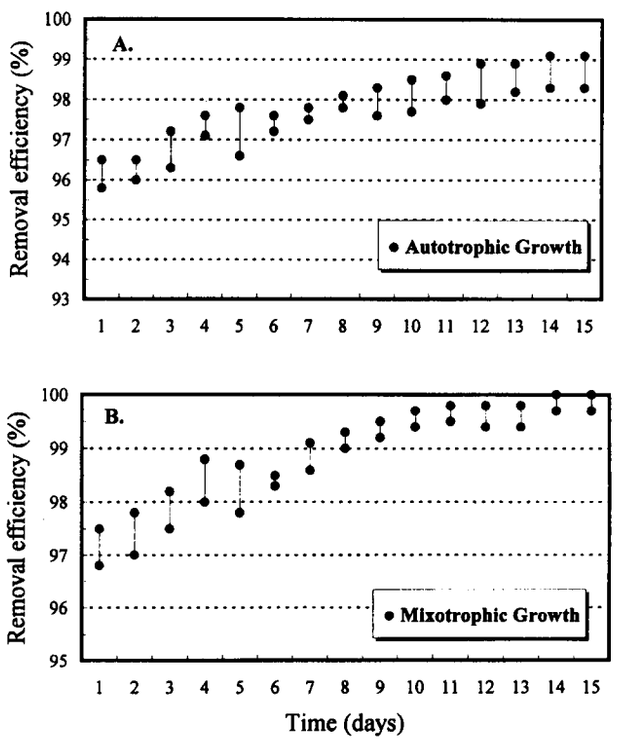

FIG. 2. H_2S Removal Efficiencies by *Thiobacillus novellus* CH 3 Biofilters: (a) in Autotrophic; (b) in Mixotrophic Environments at 36 L/h with Inlet Concentrations of 10–60 ppm at pH 7

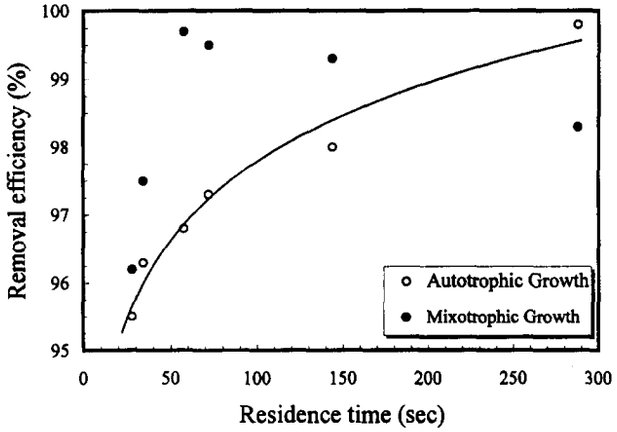

FIG. 3. H_2S Removal Efficiency as Function of Residence Time at Inlet Concentration of 60 ppm

h. The removal efficiency of the autotrophic biofilter decreased significantly with decreases in H_2S residence time. By contrast, the mixotrophic biofilter exhibited a different removal pattern. The removal efficiency increased with H_2S residence time in the range of 28–58 s (equivalent to flow rates from 185 to 90 L/h). When the residence time was longer than 58 s, the removal efficiency decreased with further increases in the H_2S residence time. Under all operating conditions except for residence time of 288 s, the mixotrophic biofilter achieved higher removal efficiencies than the autotrophic biofilter. The cells obtained energy derived from hydrogen sulfide and glucose oxidation in mixotrophic environments. Based on our results and previous studies, it appears that glucose served as an additional carbon source besides CO_2 during mixotrophic growth. Leefeldt and Matin (1980) showed that at long residence times some 30–50% more glucose was used in energy generation by *T. novellus*; hence, less H_2S was utilized by the oxidation to provide energy. By contrast, during short residence times less glucose (approximately 15%) was used in energy generation suggesting that *T. novellus* would oxidize more H_2S to provide energy for survival (e.g., 58 s) (Leefeldt and Matin 1980).

Identification of H_2S Removal Products

To understand H_2S removal by *T. novellus* CH 3 in various physiological situations, the sulfate, sulfite, and sulfide concentrations in the middle layer of the biofilter were monitored after 72 h of operation. Elemental sulfur also was measured but it was always below detection limits (0.1 mg/L). Table 2 shows the mass balance of sulfur in the biofilter, after the biofilter was operated continuously with the inlet of 60 ppm H_2S at residence times of 58 or 288 s for 3 days. When the biofilter was operated in mixotrophic environments, the predominant metabolic product was sulfate, which thus accounted for 97.6% of the total H_2S conversion at a residence time of 58 s. At a residence time of 288 s, sulfate accounted for only 73.5%. When the biofilter was operated under autotrophic environments, the same metabolic products were found; however, H_2S almost was converted to sulfate regardless of the residence time, e.g., 99.3% at 58 s and 98.0% at 288 s. The bioconversion of aerobic sulfide removal pathway by *Thiobacillus sp.* was suggested by Buisman et al. (1990)

$$S^{=} \rightarrow S^{0} \rightarrow SO_3^{=} \rightarrow SO_4^{=}$$

It is, therefore, indicated that the nearly complete oxidation of sulfide under autotrophic conditions at all residence times was an artifact of sulfide being the only source of energy. Because the residence time strongly influences H_2S removal efficiency, the optimal residence time should be held at either 288 or 72 s, depending on which biofilter condition is present.

TABLE 2. Sulfur Mass Balances in Biofilters in Mixotrophic and Autotrophic Environments at 60 ppm H_2S at pH 7

Residence time (s) (1)	H_2S removed (g S/kg bead) (2)	$SO_4^{=}$ produced (g S/kg bead) (3)	$SO_3^{=}$ produced (g S/kg bead) (4)	$S^{=}$ produced (g S/kg bead) (5)
		(*a*) Mixotrophic Biofilter		
58	1.103	0.989 (97.6%)	0.018 (1.8%)	0.004 (0.4%)
288	0.200	0.147 (73.5%)	0.049 (24.5%)	0.005 (2.5%)
		(*b*) Autotrophic Biofilter		
58	0.983	0.976 (99.3%)	0.008 (0.8%)	0.003 (0.3%)
288	0.203	0.199 (98.0%)	0.003 (1.5%)	0.001 (0.5%)

Kinetic Analysis

As the foregoing studies show, immobilized *T. novellus* CH 3 possessed an excellent ability to degrade H_2S, especially in mixotrophic environments. Kinetic analysis was performed to determine the enzymatic affinities for H_2S in the experimental biofilters. Results obtained using regression methods are shown in Fig. 4, along with corresponding regression equations. The H_2S half-saturation constants of autotrophic and mixotrophic biofilters were 78.2 and 69.2 ppm, respectively. The maximum removal capacities were 2.0 and 1.9 g S/d per kg bead. Note that the half-saturation constant (69.2 ppm) of the mixotrophic biofilter was smaller than that of the autotrophic biofilter (78.2 ppm). If we infer a physical meaning for K_s analogous to enzymatic kinetics, a decrease in K_s suggests an enhancement in biomass affinity for H_2S. Hence, the *T. novellus* CH 3 biofilter operation in the mixotrophic environment enhanced H_2S removal over autotrophic operations. In addition, the enzymatic affinity in the continuous trials (i.e., half-saturation constants are 69.2 and 78.2 ppm, respectively) were higher than those in the batch experiments (i.e., half-saturation constants are 74.5 and 84.3 ppm, respectively), regardless of whether the biofilter was operated under autotrophic or mixotrophic conditions. From a microbial physiological viewpoint, the studies brought into focus differences in the regulation of bacterial enzyme expression in different environments. This observation is in accordance with Leefeldt and Matin (1980) who showed that the enzymes in *T. novellus* may be repressed under nutrient-excess conditions of batch culture and activated under the nutrient-limited conditions of continuous culture.

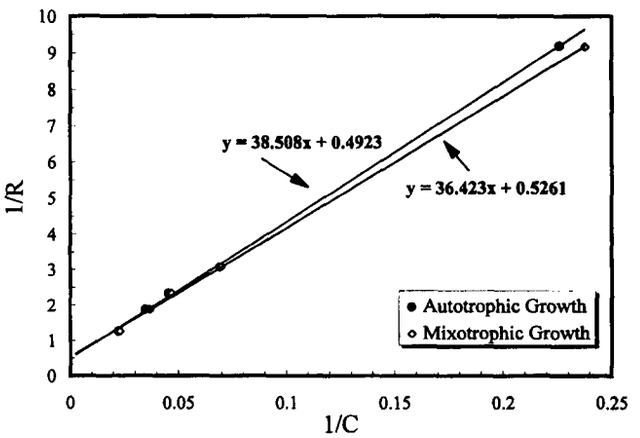

FIG. 4. Relationship between H_2S Degradation $1/R$ and $1/C$ in Biofilters

Criteria for Design of Scale-Up Biofilters

Complete H_2S removal can be achieved only at less than critical inlet load. If this critical inlet load is exceeded, H_2S is detected continuously at the outlet of the biofilter. The system load is defined as the amount of inlet gas per unit of time per weight of packing material (g S/d per kg bead). Thus, inlet gas concentrations play an important role in the design of a scale-up biofilter if the weight of the packing material and the gas-flow rate are constant. Finding the maximum inlet concentration and the optimal inlet load therefore becomes important for the operation of a biofilter. The relationship between the maximum inlet concentration and space velocity for H_2S removal is shown in Figs. 5(a and b). The values shown in Fig. 5 also are listed in Table 3. At a space velocity of 64 h^{-1} (i.e., flow rate, 72 L/h), the mixotrophic biofilter tolerated higher loads than autotrophic biofilter. Although mixotrophic biofilter removed more H_2S than autotrophic biofilter, the former seems to be superior to the later only when a low emission concentration (<0.1 ppm) was required. Therefore, the mixotrophic biofilter operations were superior to the autotrophic biofilter operations when strict emission concentration constraints were imposed.

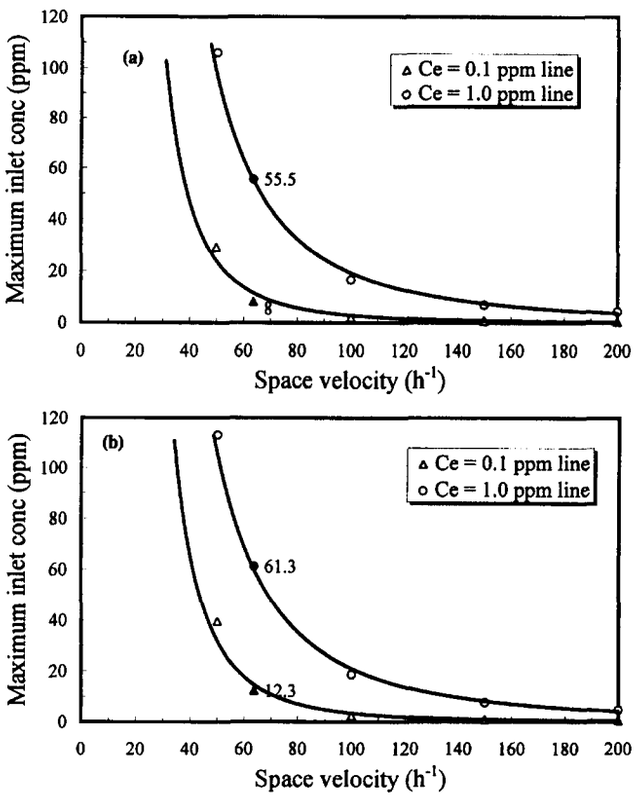

FIG. 5. Relationship between Maximum Inlet Concentration and Space Velocity for H_2S Removal by *Thiobacillus novellus* CH 3 Biofilters: (a) in Autotrophic; (b) in Mixotrophic Environments

TABLE 3. Maximum Inlet Concentrations and Critical Loads in Mixotrophic and Autotrophic Biofilters at Target Emission Concentrations of 0.1 or 1 ppm at 64 h^{-1}

Emission concentration (ppm) (1)	Maximum inlet concentration (ppm) (2)	Critical load (g S/d per kg bead) (3)
(*a*) Mixotrophic Biofilter		
0.1	12.3	0.070
1	61.3	0.346
(*b*) Autotrophic Biofilter		
0.1	8.0	0.045
1	55.5	0.313

CONCLUSIONS

The optimal condition of H_2S removal by *T. novellus* CH 3 biofilter was found at pH 7 and 26°C. In continuous trials, the mixotrophic biofilter achieved steady-state condition in a shorter time and exhibited higher efficiency in removing H_2S than the autotrophic biofilter. The mixotrophic biofilter achieved greater than 99.5% removal efficiency after 10-day operation even at H_2S concentration as low as 10 ppm. The main product of H_2S oxidation by *T. novellus* CH 3 was identified as sulfate. The formation ratio of sulfate to sulfide in the mixotrophic biofilter depended on the residence time of H_2S. Longer residence time benefited the H_2S removal in the autotrophic biofilter, but the optimal residence time was found to be approximately 58 s in the mixotrophic biofilter. The efficiency of sulfide oxidation and the products formed suggest that different physiological regulatory mechanisms affect enzyme synthesis and expression in the mixotrophic biofilter under various H_2S flow rates. When a biofilter concurrently received glucose and H_2S, it exhibited a higher H_2S affinity than a biofilter receiving H_2S only. From a design standpoint, the mixotrophic biofilter possesses a removal capacity similar to that of the autotrophic biofilter when high emission concentration is permitted. However, the mixotrophic biofilter is superior to the autotrophic biofilter, when a stringent emission limit is required.

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C_e = outlet concentration (ppm);
C_{ln} = logarithmic mean concentration of H_2S at inlet and outlet of biofilter (ppm);
C_o = inlet concentration (ppm);
F = gas flow rate (m^3/d);
K_s = half-saturation constant (ppm);
K_T = reaction rate at T°C (g S/m^3 per day);
K_{20} = reaction rate at 20°C (g S/m^3 per day);
L = packing height (m);
R = removal rate (g S/d per kg dry bead);
S_a = column cross section (m^2);
T = temperature (°C);
V_m = maximum removal rate (g S/d per kg dry bead);
α = conversion coefficient (kg dry bead/g S); and
θ = temperature-dependency coefficient.

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