Co-treatment of hydrogen sulfide and methanol in a single-stage biotrickling filter under acidic conditions

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Abstract

Biofiltration of waste gases is cost-effective and environment-friendly compared to the conventional techniques for treating large flow rates of gas streams with low concentrations of pollutants. Pulp and paper industry off-gases usually contain reduced sulfur compounds, such as hydrogen sulfide and a wide range of volatile organic compounds (VOCs), e.g., methanol. It is desirable to eliminate both of these groups of compounds. Since the co-treatment of inorganic sulfur compounds and VOCs in biotrickling filters is a relatively unexplored area, the simultaneous biotreatment of H_2S and methanol as the model VOC was investigated. The results showed that, after adaptation, the elimination capacity of methanol could reach around 236 g m^{-3} h^{-1} with the simultaneous complete removal (100%) of 12 ppm H_2S when the empty bed residence time is 24 s. The pH of the system was around 2. Methanol removal was hardly affected by the presence of hydrogen sulfide, despite the low pH. Conversely, the presence of the VOC in the waste gas reduced the efficiency of H_2S biodegradation. The maximal methanol removal decreased somewhat when increasing the gas flow rate. This is the first report on the degradation of methanol at such low pH in a biotrickling filter and on the co-treatment of H_2S and VOCs under such conditions.

Keywords

Acidophiles; pH; Fungi; Substrate competition; Oxygen limitation

1. Introduction

Biofiltration is an established waste gas treatment technology that may provide a cost-effective solution for many industries facing emission problems (Kennes and Veiga, 2001). A biofilter consists of a packed bed of organic or synthetic material on which a microbial film is attached. When a contaminated air stream passes through the reactor, the pollutants are transferred to the biofilm, where they are biodegraded to simple end products, such as water and carbon dioxide in the case of non-halogenated volatile organic compounds (VOCs). Instead of using large amounts of thermal energy to destroy pollutants, or removing pollutants by transfer from one phase to another, biofilter systems harness the natural ability of microorganisms to degrade organic and inorganic contaminants biochemically into environmentally harmless end products at ambient temperature. Under adequate conditions, gas-phase bioreactors are more efficient than non-biological treatment processes for VOC removal (Kastner and Das, 2005). A biotrickling filter works in a similar manner to a biofilter, except that an aqueous phase is continuously trickled over the packing, and the filter bed is made of some synthetic or inert material, like plastic rings, open pore foam, or lava rock. The

trickling solution contains essential inorganic nutrients such as nitrogen, phosphorous, and potassium, and is usually recycled.

To date, most lab-scale biofiltration studies address the removal of single pollutants under constant operating conditions. Such conditions are highly unusual at wastewater treatment plants and some other facilities. For instance, the malodorous emissions into the atmosphere from a pulp mill originate mainly from cooking, pulp washing, recovery boiler, evaporation, bark boiler, white liquor preparation, lime kiln, and pulp drying. These emissions tend to be a complex mixture of H_2S and other reduced sulfur compounds (such as dimethyl sulfide, dimethyl disulfide, and methyl mercaptan), as well as VOCs (such as methanol, terpenes, alcohols, phenol, ketones, and formaldehyde). The actual composition and individual concentrations often vary over time. In addition to being malodorous and toxic, some of these gases also undergo photochemical reactions in the atmosphere, contributing to the formation of photochemical oxidants, principally ozone.

Relatively little is known on the treatment of off-gases that contain both H_2S and VOCs. One problem encountered is that, as the sulfur in hydrogen sulfide is converted to sulfuric acid, the pH of the biofilm decreases. If the pH declines rapidly, biological activity in the biofilter may be inhibited, thereby reducing treatment effectiveness for organic compounds and sulfide, although H_2S is generally oxidized by *Thiobacillus* species that exhibit optimum activity at relatively acidic pH. However, most *Thiobacillus* species are autotrophic organisms and, therefore, many of them do not use VOCs as a carbon source for growth. Most known heterotrophic bacteria capable of consuming VOCs prefer neutral pH, and heterotrophic VOC-degraders are often more inhibited by acidification than H_2S-degraders. In addition, acid conditions may hasten the deterioration of organic support media. These apparently conflicting pH optima for microbial activity are a challenge for developing bioreactors for the simultaneous removal of both H_2S and VOCs.

One solution is the treatment in a two-stage process as proposed by Chitwood et al. (1999). In the first stage, H_2S is oxidized in a biotrickling filter in which the pH drops as a result of H_2SO_4 accumulation. The H_2S-free off-gas is then passed through a neutral-pH biofilter for the removal of VOCs. Considerable savings could possibly be made if H_2S and VOC removal was combined in a single bioreactor. The same authors also investigated another solution for the treatment of mixed hydrogen sulfide and organic vapors in a rock packed pilot-scale biofilter (Chitwood and Devinny, 2001). The removal efficiencies of H_2S and VOC reached at pH 4 were comparable to the values expected for a neutral-pH biofilter. However, lava rock is susceptible to dissolution at low-pH conditions (around 4). Recently, Cox and Deshusses (2002) reported that H_2S and toluene can be effectively treated simultaneously in a single-stage biotrickling filter. The pH of operation (4.5 or 7.0) did not greatly affect the performance of H_2S and toluene removal, except that at pH 4.5, the startup phase of toluene degradation was relatively long. Recent research at publicly owned treatment works has shown that H_2S and low concentrations of VOCs can be co-treated in biofilters without pH control.

In our previous research, the autotrophic biodegradation of hydrogen sulfide as single pollutant was studied in a low-pH biotrickling filter (Jin et al., 2005a and Jin et al., 2005b). However, hydrogen sulfide and VOCs such as methanol, formaldehyde, methyl ethyl ketone, are often found together in waste air streams. Since the co-treatment of

H_2S and VOCs in biotrickling filters is a relatively unexplored area, and autotrophic microorganisms do not use methanol as a carbon source for growth, the objective of this research was to investigate the feasibility of using a single-stage low-pH biotrickling filter to treat a mixture of methanol and H_2S. Methanol was added to an originally autotrophic low-pH H_2S-degrading reactor to determine to what extent the organic compound could be removed.

2. Material and methods

2.1. Experimental setup

The schematic of the biotrickling filter used in this study is shown in Fig. 1 and has been described previously in detail (Jin et al., 2005a). It is a cylindrical packed bed reactor made of glass, 75 mm in diameter and 700 mm in height, filled with polypropylene Pall rings of a nominal height of 15 mm. The total height of the packed bed was 640 mm. The Pall ring bed had an initial porosity of 91% and a specific surface area of 350 $m^2\ m^{-3}$. This inert synthetic packing material was used to exclude any carbon source other than methanol and prevent complications arising from bed compaction and aging over the experimental period. The glass column contained four equidistant sampling ports. All fittings, connections and tubings were made of Teflon. H_2S was introduced by passing the gas stream over a H_2SO_4 solution into which a solution of Na_2S was dripped. Gas phase H_2S concentrations were regulated by changing the Na_2S concentration and/or dripping rate. Methanol was introduced into the gas by saturating a side air stream sparged into a bottle filled with pure methanol. The resulting waste gas was introduced through the bottom of the column for counter-current flow operation (Fig. 1). The gas flow rate was maintained constant at 7 $l\ min^{-1}$, corresponding to an empty bed residence time (EBRT) of 24 s. The aqueous mineral medium was continuously recirculated over the packed bed using a peristaltic pump (model 323E/D, Watson-Marlow Limited, Falmouth Cornwall, England) at a constant volumetric flow rate of 2.77 $l\ h^{-1}$. The nutrient solution of the biotrickling filter was renewed every day. The biotrickling filter's performance was estimated by calculating the elimination capacity and removal efficiency at different loads, according to equations defined in the literature (Kennes and Veiga, 2001). All the experiments were conducted at room temperature (20–25 °C).

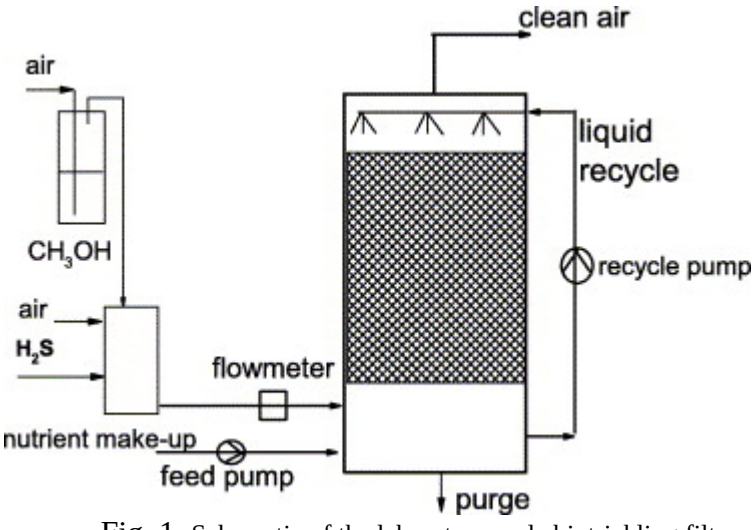

Fig. 1. Schematic of the laboratory scale biotrickling filter.

2.2. Analytical methods

The concentration of methanol in the gas phase was measured with a gas chromatograph Hewlett–Packard 5890 series II equipped with a flame ionization detector (FID). The characteristics of the TRACER TR-WAX column were: 0.32 mm internal diameter, 50 m long with 1.2 μm thickness. The gas flow rates were as follows: H_2, 30 ml min^{-1}, and air, 300 ml min^{-1}. The inlet and outlet gas streams, as well as air between the biofilter sections, were sampled. Helium was used as the carrier gas at a flow rate of 2.0 ml min^{-1}. The methanol concentration was determined at the oven temperature of 120 °C and using a FID at 250 °C. Inlet and outlet H_2S concentrations were determined using a gas sensor (Dräger Sensor XSEC H_2S HC6809180). The pH of the nutrient solution was measured with a Crison pH-meter 507, using a combined glass electrode. Samples of packing from the biotrickling filter were prepared for observations under the electron microscope according to a standard procedure as previously reported (Jin et al., 2005b). Examination was performed with a JEOL JSM-6400 SEM working at a voltage of 20 kV and a working distance of 15 mm, and with Oxford Instruments EDX equipment. Samples were photographed extensively to ensure that representative images of the filter bed had been taken. From the difference between the inlet and outlet values of a manometer connected to the inlet and outlet ports of the reactor, pressure drop was calculated and normalized per meter packing height.

3. Results and discussion

3.1. Initial performance of an originally autotrophic H_2S-treating biotrickling filter after methanol addition

Methanol was supplied in the range of 18 to 81 ppm to allow for the determination of a possible positive or negative effect of an organic carbon source as CH_3OH on H_2S removal in an originally autotrophic system.

Fig. 2 shows that when CH_3OH was added at concentrations ranging from 18 to 81 ppm, a gradual decrease in the removal efficiency of H_2S was observed as the gas concentration of CH_3OH increased. The maximum elimination capacity of H_2S dropped from 23.8 g m^{-3} h^{-1} at the lowest methanol concentrations to 6.4 g m^{-3} h^{-1} at the highest VOC concentration. Autotrophic microorganisms were originally dominant in the biotrickling filter, using CO_2 as carbon source instead of CH_3OH for H_2S removal, but the presence of CH_3OH caused a gradual growth of heterotrophic organisms and a decrease of the autotrophic activity as evidenced by the decrease of H_2S removal.

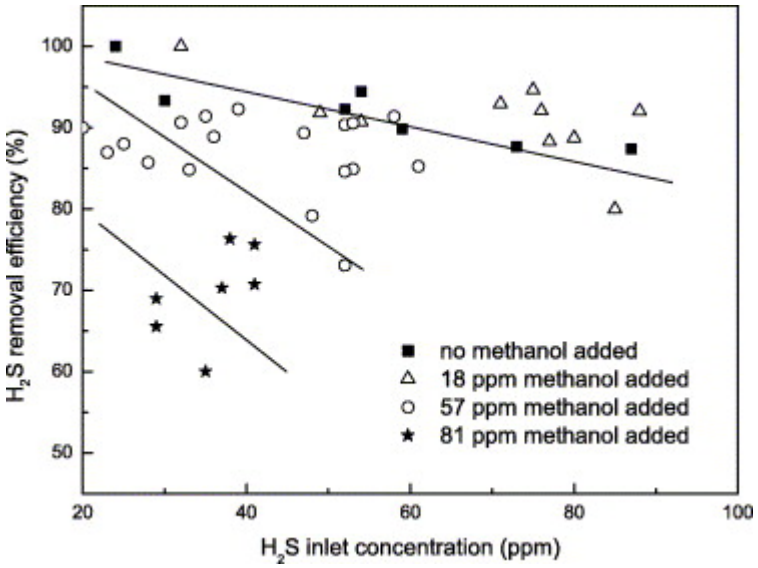

Fig. 2.

Influence of methanol on the performance of a biotrickling filter removing H_2S.

Conversely, the elimination capacity of CH_3OH did gradually increase from 2.7 to 11 g m^{-3} h^{-1} during that same period (Fig. 3). This value is much smaller than the maximum elimination capacities reported in the literature, which range from 50 to 250 g m^{-3} h^{-1} (Sologar et al., 2003). This could result from the very low pH of the filter bed, around 2, which is generally considered not optimum for bacterial methanol degradation. The optimum pH for VOC-degrading microorganisms is usually around 7. Nevertheless, adaptation to acidic conditions is possible as will be shown below in subsequent experiments. On the other hand, only H_2S was initially fed to the reactor (Jin et al., 2005a and Jin et al., 2005b) and therefore hardly any methanol biodegrading microorganisms were originally present in the filter bed, which is another reason that explains the limited methanol removal. The addition of CH_3OH allowed the gradual growth of heterotrophs utilizing that VOC as carbon source. The removal efficiency of CH_3OH did first increase from 58% to 65% and then decreased to 52% at inlet concentrations of 18, 57, and 81 ppm, respectively while maintaining the inlet H_2S-concentration at 12 ppm (Fig. 3).

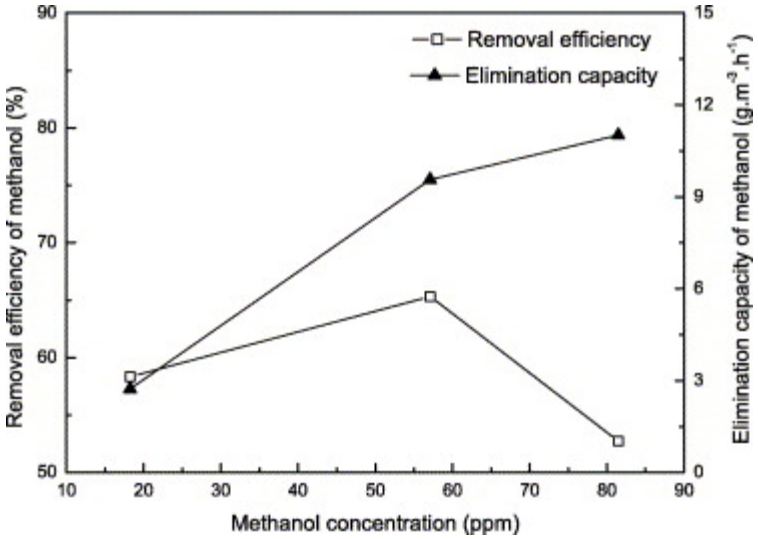

Fig. 3.

Removal efficiency and elimination capacity of CH_3OH.

3.2. Improvement of methanol removal after new inoculation

In order to try to improve the removal of methanol, fresh activated sludge was inoculated into the reactor. After that, the removal of methanol improved and the methanol inlet concentration was then increased. The pH of operation was relatively constant, around 2, as a result of H_2S degradation. During the first 20 d, although the inlet concentration was increased daily, the removal efficiency always remained 100% (Fig. 4). This means that the methanol degrading microorganisms started to grow after the new inoculation. At the same time, the removal of H_2S reached 100% at an inlet concentration of 12 ppm. After this new start-up period, the removal efficiency of methanol remained around 95% with the inlet concentrations between 450 and 700 ppm in the following steady states.

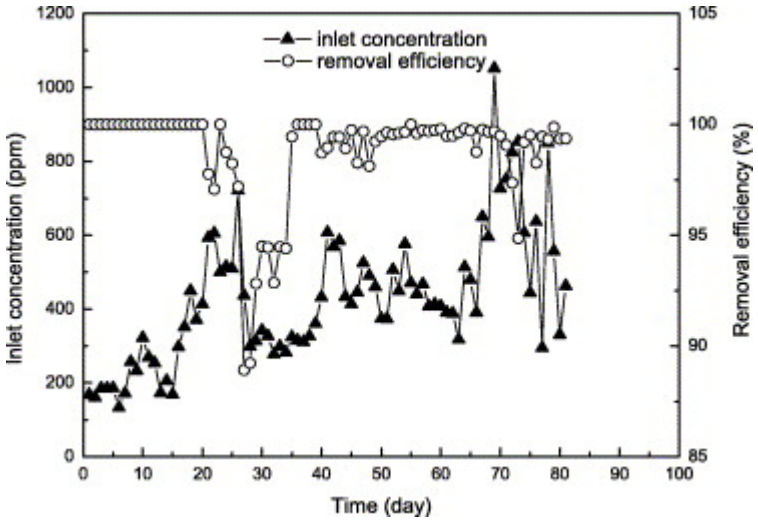

Fig. 4.

Methanol removal with time after inoculation of fresh activated sludge.

To establish operating criteria necessary to scale-up the biotrickling filter, the relationship between the inlet loading of methanol and the elimination capacity was estimated. The results are reported in Fig. 5. The elimination capacity is defined as the amount of pollutant degraded per unit time, normalized to the volume of packed bed. As shown in Fig. 5, the relationship between the load and the removal rate rises linearly and the critical load (i.e., deviation from the complete removal capacity) was not reached yet when the elimination capacity was 160 g m^{-3} h^{-1}. Besides, the removal efficiency of methanol was always above 97.5% during most of the experimental period at inlet concentrations below 1100 ppm (Fig. 5).

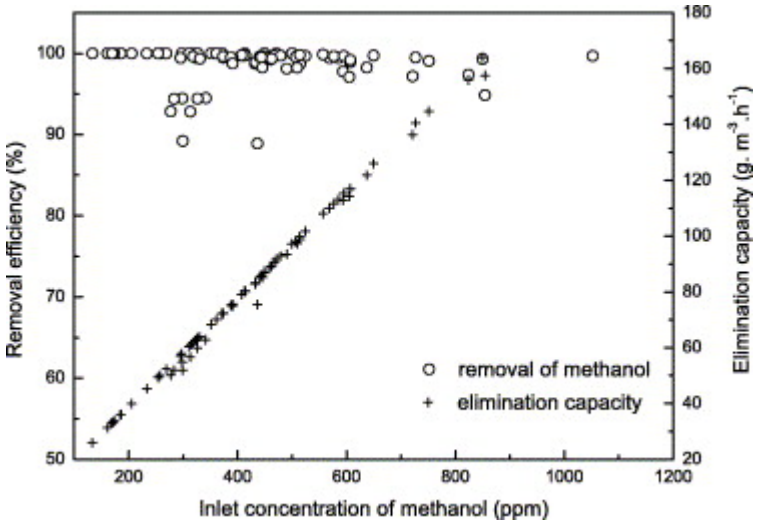

Fig. 5.

Elimination capacity of methanol versus its inlet concentration in the co-treatment of H_2S and methanol in a biotrickling filter. Removal efficiency as a function of the inlet concentration data include three months of continuous operation. The removal of H_2S reached 100% with an inlet concentration of 12 ppm.

Until now, there is no report on the co-treatment of methanol and H_2S at such low pH. Thus, further research about this topic is quite necessary. This does also show that adaptation of heterotrophic VOC-degrading microorganisms to very low pHs is sometimes possible. The same was observed previously in an alkylbenzene-treating biofilter, in which bacteria as *Pseudomonas* sp. and *Bacillus* sp. were able to degrade the pollutants at a pH as low as 3.5 (Veiga et al., 1999).

3.3. Effect of the gas flow rate

In Fig. 6 the measured trickling filter's elimination capacity is plotted for different inlet methanol concentrations at a constant liquid flow rate of 2.77 l h^{-1} (0.627 m h^{-1}) and at gas flow rates of 6, 7, and 10 l min^{-1}, corresponding to superficial gas velocities of 81, 95, and 136 m h^{-1} and EBRT of 28, 24, and 17 s. From this figure, it can be observed that the removal efficiency decreased when increasing the gas flow rate over all the concentration range studied.

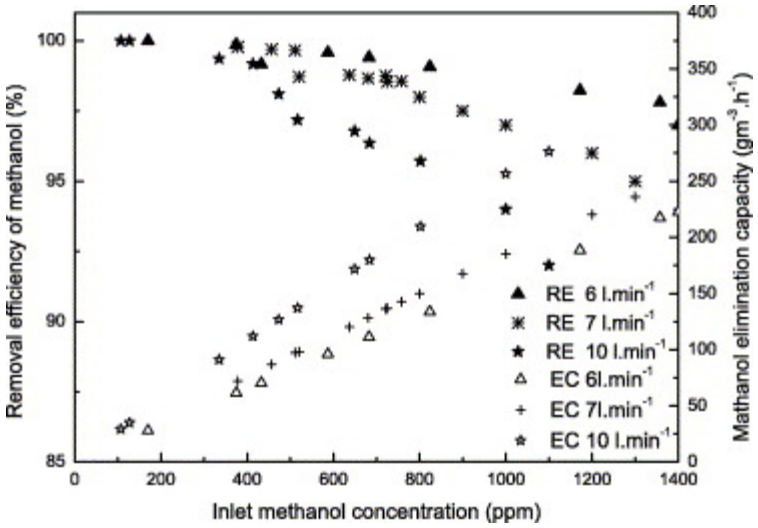

Fig. 6.

Removal efficiency of methanol in the biotrickling filter as a function of the inlet concentration, at different flow rates of the gas streams.

At 10 l min^{-1} a maximum methanol elimination capacity of 276 g m^{-3} h^{-1} was obtained, while at 6 and 7 l min^{-1} the maximum elimination capacities were 222 and 236 g m^{-3} h^{-1}, respectively. At the same time, the elimination capacity of H_2S was 2.5 g m^{-3} h^{-1}. It seems that the elimination capacity of methanol increased with the gas flow rate. This may be due to the high turbulence at high gas flow rates making the liquid film become thinner and enhancing the mass transfer of methanol.

3.4. Substrate competition and stratification of biodegradation

In order to gain insight in the biodegradation mechanisms of the H_2S and methanol mixture, their concentrations were measured at different heights in the column. Fig. 7 shows concentration profiles of methanol and H_2S along the length of the biotrickling filter. For 25 ppm H_2S and 500 ppm methanol, the results show that methanol was completely eliminated in the first two-thirds of the column with most of the removal (75%) taking place over the first one-third, while H_2S was degraded at a quite constant rate over the complete height of the column. These results show a stratification in terms of biodegradation. Methanol was metabolized before H_2S. Two hypotheses can be suggested regarding the microbial populations: (1) there was competition between populations and the different populations colonizing the Pall ring-packed biotrickling filter were either specialized in the elimination of methanol or in H_2S removal; (2) there was competition between substrates and, in such case, the bacterial community remained roughly the same over the height of the column, but the more easily biodegradable methanol was used first for microbial metabolism when it was present in the gaseous effluent.

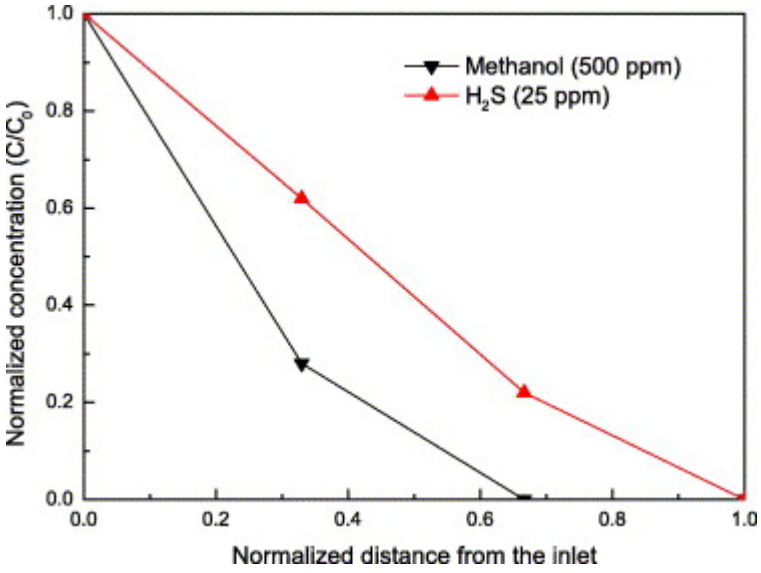

Fig. 7.

Methanol and H_2S concentration profiles along the length of the biotrickling filter.

Other researchers observed a similar behavior when feeding mixed pollutants, although in all of those studies, only VOC mixtures were fed and no inorganic pollutants as H_2S. Ergas and coworkers observed that toluene elimination occurred in the first centimeters of the column and dichloromethane (DCM) elimination occurred in the second half of the column when treating a mixture of toluene and DCM in a biofilter (Ergas et al., 1996). The authors proposed a stratification in terms of biodegradation and suggested that two different microbial communities colonized the reactor at steady state. Deshusses et al. (1999) observed a stratification in terms of degradation when treating a mixture of ethyl acetate and toluene. Ethyl acetate was degraded in the inlet part of the column and toluene elimination occurred in the second half of the column. Furthermore, the authors highlighted that microorganisms that colonized the first centimeters of the column had the potential to degrade toluene. They suggested that substrate competition occurred and that the microorganisms degraded preferentially the more easily biodegradable compound. Aizpuru and coworkers also reported that a stratification of biodegradation occurred in a biofilter treating a mixture of methanol, acetone, methyl ethyl ketone, methyl isobutyl ketone, butyl and ethyl acetates, toluene, ethylbenzene, xylene, dichloromethane, and 1,2-dichloroethane (Aizpuru et al., 2001). The oxygenated compounds were metabolized before the aromatic and halogenated ones. Hwang et al. (2003) reported the degradation of ethyl acetate and toluene mixtures in a biofilter using different combinations of bacterial cultures and changes in the degradabilities of ethyl acetate and toluene induced by substrate combination and microbial community competition were observed. In our present study, however, if the second hypothesis mentioned above is correct, the H_2S-degrading population should be facultative heterotrophic methanol degrader as well. The existence of the heterotrophic H_2S-degraders has been reported in the literature (Lens and Pol, 2000). Nevertheless, it is expected that both heterotrophic methanol degraders and autotrophic H_2S degraders are present as two different populations in the reactor. Since the bioreactor was originally fed H_2S as single pollutant, the autotrophic population is most probably present in the full filter bed volume explaining the linear removal rate observed in Fig. 7, while the heterotrophic population, developing after the inoculation of fresh sludge, colonized the

inlet zone of the packing explaining the faster methanol removal in that zone (Fig. 7). Preliminary data on the microbiological characterization of the biofilm suggest that the main acid-tolerant methanol degrader in the inlet zone of the filter bed is a yeast according to microscopic observations and batch experiments.

3.5. Oxygen limitation

Oxygen limitation led to the partial transformation of H_2S to elemental sulfur with the simultaneous removal of methanol. Fig. 8 shows spent Pall rings after introduction of methanol into the originally autotrophic biotrickling filter. The rod-shaped material in the spent Pall rings was mainly condensed elemental sulfur, as was also confirmed by the subsequent elemental analysis. Compared to the results obtained during the autotrophic H_2S biodegradation, the sulfur content in the present experiment was higher than in that previous study, reaching values of 70% and 62%, respectively. Sulfur production from the partial oxidation of sulfide instead of the complete oxidation to sulfate may be due to oxygen limitation caused by preferred methanol consumption because of its good biodegradability. According to the stoichiometry of the aerobic biological sulfide oxidation, oxygen is the key parameter that controls the level of oxidation, according to the following equations:

$$2HS^- + O_2 \rightarrow 2S^o + 2OH^- \quad \Delta G^o = -129.50 \text{ kJ mol}^{-1}2$$

$$2HS^- + 4O_2 \rightarrow 2SO_4^{2-} + 2H^+ \quad \Delta G^o = -732.58 \text{ kJ mol}^{-1}$$

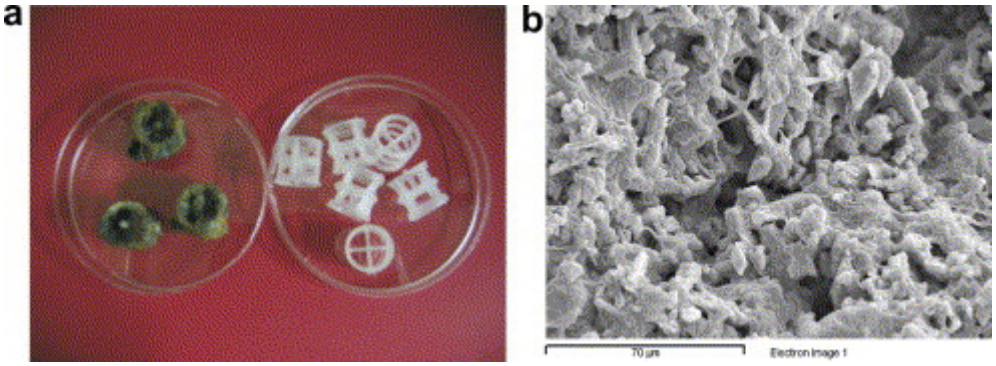

Fig. 8.

Pictures of Pall rings. (a) Clean Pall rings (right) and rings covered with biomass (left). (b) SEM photo of Pall rings from a bioreactor treating methanol and H_2S.

Sulfur production (Eq. (1)) results from the partial oxidation of sulfide instead of a complete oxidation to sulfate (Eq. (2)) when oxygen is limited. Additionally, lower energy consumption is required because the oxidation to sulfur requires four-fold less oxygen.

Other researchers also observed similar results. Buisman et al. (1990) reported that, at sulfide concentrations below 20 mg l^{-1}, the oxygen concentration should be kept low (below 1 mg l^{-1}) to limit sulfur oxidation to sulfate. Janssen et al. (1995) found that the optimal oxygen to sulfide molar ratio to improve the sulfur production was about 0.7. The same authors described the performance of a sulfide-oxidizing expanded-bed

reactor that was designed for elemental sulfur formation (Janssen et al., 1997). In that reactor, the aeration of the liquid phase and the oxidation of sulfide were spatially separated. Sulfur sludge with good settling properties, which consisted mainly of elemental sulfur (92%) and biomass (2%), was obtained.

The partial oxidation of sulfide presents environmental implications as elemental sulfur can be removed by sedimentation. However, long term bioreactor operation may result in the gradual accumulation of sulfur inside the filter bed, blockage of pores and apparently channeling. This will lead to a continuous decrease of H_2S removal, as observed in a previous study on H_2S removal without methanol (Jin et al., 2005b). Moreover, when a VOC as methanol is present in the waste gas, the growth of heterotrophs is much faster than autotrophs and also contributes significantly to the clogging of the bioreactor. The filter bed with accumulated biomass and sulfur products suffers channeling problems and subsequently decreases in the performance, that may be confused with substrate competition. However, there appears to be little impact of multiple substrates on system performance once acclimation has occurred.

3.6. Pressure drop

The filter bed's pressure drop is a key aspect of biofilter performance. It affects the energy consumption of the blower, which contributes most to the operation costs. The variations of pressure drop in the filter column are shown in Fig. 9. During previous experiments on the autotrophic biodegradation of H_2S as single pollutant, the variation of the pressure drop in the biotrickling filter was negligible (Jin et al., 2005a and Jin et al., 2005b). After introduction of methanol into the bioreactor, the pressure drop did first slightly increase to around 10 mm $H_2O\ m^{-1}$ in 230 d, while the removal of methanol increased simultaneously until the pressure drop of the bioreactor reached a critical value of 20 mm $H_2O\ m^{-1}$. The pressure drop increase probably resulted from the accumulation of sulfur product and biomass due to the continuous high inlet load of methanol. Under a methanol inlet loading rate of 150 $g\ m^{-3}\ h^{-1}$, the removal efficiency of methanol first remained around 95% (Fig. 9). With the increase of pressure drop, the removal efficiency dropped steeply and finally reached 15% as the pressure drop increased to 57 mm $H_2O\ m^{-1}$. Then, a relatively high liquid flow rate of 13.9 $l\ h^{-1}$ was used for removing the excess biomass and generated sulfur. In this way, the pressure drop could be maintained again below 15 mm $H_2O\ m^{-1}$ and the performance was not affected.

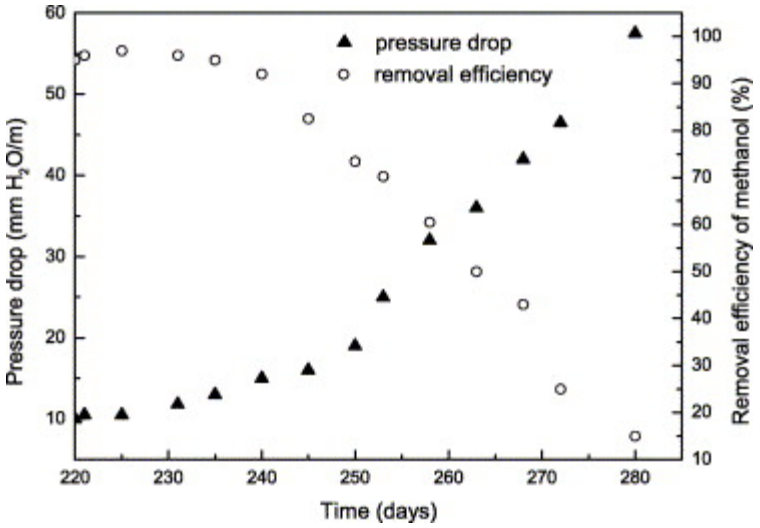

Fig. 9.

Variation of the pressure drop and performance of the biotrickling filter under a methanol inlet loading rate of 150 g m^{-3} h^{-1}.

Most of the time pressure drop increase is related to biofilm growth and clogging by biomass. For example, Liu et al. (1994) working with granular activated carbon columns for toluene removal, measured increased pressure drops of up to 1223 mm H_2O m^{-1} due to biomass accumulation resulting in airflow channeling. In general, the increase in pressure drop as a result of biomass development in biofilters can be explained by a decrease in the bed interparticle void space or the effective porosity or both and by the microbial degradation of the support matrix in the case of natural media, which result in decreased specific permeability. Although the effect of biomass accumulation on pressure drop has been reported, and has been studied in biotrickling filters treating gaseous streams (Sorial et al., 1997 and Okkerse et al., 1999), there has been little detailed, quantitative research on how to avoid this problem. Therefore, controlled formation of biomass in a trickle-bed reactor is a prerequisite to estimate its capacity and the continuity for waste gas treatment. Two ways are feasible to maintain the back pressure low and a high bioreactor performance: (1) reduce the biomass formation rate, or (2) remove the formed biomass. A reduced biomass formation rate can be achieved by limiting the supply of some nutrient, such as phosphate or potassium, although this does often also reduce the reactor's performance (Kennes and Veiga, 2002). The continuous removal of formed biomass is suitable to operate a trickle-bed reactor under steady state with respect to interfacial area and mass transfer resulting in a constant elimination capacity. This was also the option used in the present work, in which feeding the liquid phase at a relatively high flow rate allowed reducing pressure drop. Overall, the co-treatment of H_2S and methanol in a single-stage low-pH biotrickling filter packed with Pall rings is promising. However, the optimization of operational parameters such as limiting the pressure drop still needs some further research.

4. Conclusions

The results show that the co-treatment of H_2S and methanol in a single-stage low-pH biotrickling filter is feasible after growth and adaptation of acidophilic methanol-consuming populations. In the originally autotrophic biotrickling filter treating H_2S, the introduction of CH_3OH had no significant influence on H_2S removal when the inlet concentration of CH_3OH was below 18 ppm. In the range of 57–81 ppm methanol, the removal of H_2S was inhibited by the presence of CH_3OH and the maximum elimination capacity of H_2S dropped from 23.8 to 6.4 $g\,m^{-3}\,h^{-1}$. After reinoculation of the biotrickling filter with activated sludge, methanol and H_2S could successfully be treated at low pH in a single-stage biotrickling filter packed with Pall rings. The maximum elimination capacity of methanol and H_2S reached as high as 236 $g\,m^{-3}\,h^{-1}$ and 6.4 $g\,m^{-3}\,h^{-1}$, respectively. The presence of methanol in the system significantly decreased the removal rate of H_2S while the removal of methanol was not affected by the presence of H_2S, despite the low pH of 2 reached in the filter bed. However, excess biomass growth and sulfur accumulation caused a high pressure drop and consequently inhibition of the biotrickling filter's performance. This single-stage biotrickling filter would be very economical for the co-treatment of odors and toxic organic substances from wastewater treatment plants or pulp and paper industries, among others.

Acknowledgements

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