Simulation of Biomass Accumulation Pattern in Vapor-Phase Biofilters

Jin-Ying Xi,* Hong-Ying Hu, and Xian Zhang

State Key Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, China.

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Abstract

Existence of inert biomass and its impact on biomass accumulation patterns and biofilter performance were investigated. Four biofilters were set up in parallel to treat gaseous toluene. Each biofilter operated under different inlet toluene loadings for 100 days. Two microbial growth models, one with an inert biomass assumption and the other without, were established and compared. Results from the model with the inert biomass assumption showed better agreement with the experimental data than those based on the model without the inert biomass assumption thus verifying that inert biomass accumulation cannot be ignored in the long-term operation of biofilters. According to the model with an inert biomass assumption, the ratio of active biomass to total biomass will decrease and the inert biomass will become dominant in total biomass after a period of time. Filter bed structure simulation results showed that the void fraction is more sensitive to biomass accumulation than the specific surface area. The final void fraction of the biofilters with the highest inlet toluene loading is only 67% of its initial level while the final specific surface area is 82%. Identification and quantification of inert biomass will give a better understanding of biomass accumulation in biofilters and will result in a more exact simulation of biomass change during long-term operations. Results also indicate that an ideal biomass control technique should be able to remove most inert biomass while simultaneously preserving as much active biomass as possible.

Key words: biofilter; microbial growth model; inert biomass; biomass control

Introduction

OVER THE PAST TWO DECADES, biofiltration has become recognized as a cost-effective method of treating volatile organic compounds (VOC). Many full-scale biofilters have been set up and successfully used to treat different organic or odorous waste gases emitted from industrial or waste treatment processes (Swanson and Loehr, 1997; Nikiema *et al.*, 2007). However, decreases in VOC removal capacity and increases in pressure drop because of excess biomass accumulation are serious problems in biofilter applications (Alonso *et al.*, 1996, 1998). Accumulated excess biomass reduces the void fraction and specific surface area of the filter bed and changes the bed's pore size distribution (Schwarz *et al.*, 2001). Therefore, it is essential to know the characteristics and mechanisms of biomass accumulation in order to predict the impact of biomass accumulation on a biofilter's performance.

The biomass accumulation pattern in the filter bed is affected by some operating conditions, such as inlet VOC loading, nutrient feeding, and type of nitrogen source (Smith *et al.*, 1996; Deshusses and Cox, 1999; Kennes and Veiga, 2002). Many microbial growth models have been developed to describe biomass accumulation patterns under different operating conditions (Schwarz *et al.*, 2001; Song and Kinney, 2002; Iliuta and Larachi, 2004; Nukunyaa *et al.*, 2005; Silva *et al.*, 2010). Among these models, however, only a few have considered inert biomass, that part of a biomass composed of cells without biological activity. Although all the models seem to successfully predict the biofilter performance, the microbial growth patterns are quite different with and without an inert biomass assumption (Okkerse *et al.*, 1999). According to a model without an inert biomass assumption, total biomass will reach a constant value after a long period of operation. However, a model with an inert biomass assumption shows that the total biomass will increase continuously no matter how long the biofilter is operated.

One reason inert biomass is sometimes ignored is because measurements of active or inert biomass are rather difficult (Shim and Lewandowski, 2002; Mitchell *et al.*, 2004). Another possible reason is that a consideration of inert biomass would make model resolution and calculation more complicated.

*Corresponding author: State Key Laboratory of Environmental Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing, 100084, China. Phone: +86-10-62797163; Fax: +86-10-62797163; E-mail: xijinying@tsinghua.edu.cn

Although some researchers have noted that inert biomass affects the biomass accumulation patterns as well as the reactor performance (Liu, 2002; Song and Kinney, 2005), there are few specific studies on the existence of inert biomass and its impact on biofilter performance. The aim of this study is to investigate the existence of inert biomass and its effect on biomass accumulation patterns and structure change in filter beds. Four biofilters were operated for more than 100 days, and the total biomass during the period of operation was monitored. Two microbial growth models, one with an inert biomass assumption and the other without, were established and compared. The change in the filter bed structure due to biomass accumulation was analyzed based on simulation results.

Materials and Methods

Experimental setup

Four parallel biofilters, identified as #1, #2, #3 and #4, were built for this experiment. Each biofilter column had an inner diameter of 120 mm and the height of each filter bed was 200 mm. Wood chips (10–40 mm in length; 1–3 mm in width) and propylene spheres (25 mm in diameter) were mixed (volume ratio 3:2) and packed into the filter beds. The void fraction of the filter beds was 0.60 at the beginning of the operation period. The detailed structure of the experimental system was similar to the experimental system in our previous study (Xi *et al.*, 2006).

Operating conditions

After being inoculated with activated sludge taken from a wastewater treatment plant, the four biofilters were fed with toluene gas and operated continuously for more than 100 days. The operating conditions during this period are shown in Table 1.

The experimental period was divided into two phases. In Phase I (Days 1–50), the inlet toluene concentrations of the four biofilters were similar and maintained at $\sim 1000 \text{ mg/m}^3$. In Phase II (Days 51–100), the inlet toluene concentrations of the four biofilters were set to different levels (see Table 1). During the operation period, a solution containing nitrate and other nutrients was sprayed onto the filter beds to ensure that

no nutrient limitation existed. The composition of the solution was same as that used in our previous study (Xi *et al.*, 2006).

Analytical methods

During the experimental period, the inlet and outlet gaseous toluene concentrations were analyzed by a gas chromatograph, and the pressure drops of the filter beds were monitored intermittently by a water manometer. The detailed procedure and conditions were the same as those in our previous study (Xi *et al.*, 2006). To estimate the variation in the total biomass concentration (Okkerse *et al.*, 1999), the total weight of wet biofilm in the filter bed was determined by removing the weight of the empty column and wet packing media from the weight of total biofilter column. The moisture content of the biofilm was measured during the period of operation and the total biomass concentration in dry weight was then estimated.

Model Development

Microbial growth model with inert biomass assumption

Assuming that the total biomass in the filter bed consisted of active biomass and inert biomass, the total biomass concentration X_t can be expressed by the following equation:

$$X_t = X_a + X_i \quad (1)$$

where X_t is the total biomass concentration in the filter bed (g/m^3), X_a is the active biomass concentration (g/m^3), and X_i is the inert biomass concentration (g/m^3). The variation of X_a and X_i can be expressed as

$$\frac{dX_a}{dt} = Yr - bX_a \quad (2)$$

$$\frac{dX_i}{dt} = \beta bX_a \quad (3)$$

where Y is the yield coefficient of the active biomass (g cell/g toluene), r is the toluene removal rate ($\text{g/m}^3/\text{h}$), b is the shear/decay coefficient (h^{-1}), β is the ratio of produced inert biomass to lost active biomass (dimensionless), and t is time (h). Based on Equations (1), (2), and (3), the following equations can be drawn:

$$X_a = \left(X_{a0} - \frac{Yr}{b} \right) e^{-bt} + \frac{Yr}{b} \quad (4)$$

$$X_i = \beta \left(\frac{Yr}{b} - X_{a0} \right) e^{-bt} + \beta Yrt + \beta X_{a0} + X_{i0} - \beta \frac{Yr}{b} \quad (5)$$

$$X_t = \left(X_{a0} - \frac{Yr}{b} \right) (1 - \beta) e^{-bt} + \beta Yrt + \beta X_{a0} + X_{i0} + (1 - \beta) \frac{Yr}{b} \quad (6)$$

where X_{a0} is the initial active biomass concentration when $t=0$ (g/m^3) and X_{i0} is the initial inert biomass concentration when $t=0$ (g/m^3).

Microbial growth model without inert biomass assumption

Assuming that there was no inert biomass in the filter bed, the parameter X_{i0} and β would be equal to zero, and Equation (6) could be simplified as

TABLE 1. OPERATING CONDITIONS OF THE FOUR BIOFILTERS

Items or parameters	Value
Room temperature	20°C–25°C
Designed inlet toluene concentration	In Phase I (0–50 d): 1000 mg/m^3 In Phase II (51–100 d): Biofilter #1: 1000 mg/m^3 , Biofilter #2: 600 mg/m^3 , Biofilter #3: 300 mg/m^3 , Biofilter #4: 100 mg/m^3
Flow direction	Upflow
Flow rate	0.3 m^3/h
Empty bed retention time	27 s
Superficial velocity	26.5 m/h
Nutrient feeding	Spray 120 mL solution every 8 h

$$X_t = \left(X_{a0} - \frac{Yr}{b} \right) e^{-bt} + \frac{Yr}{b} \quad (7)$$

where all the items are defined as they were for Equation (6).

Filter bed structure model

The filter bed structure model is similar to the model using parallel pipes created by Alonso and Suidan (1998). Assuming that biofilm density is constant during the period of operation, the relationship between the total biomass concentration (X_t) and the filter bed structure parameters can be expressed as

$$X_t = X_f \cdot (\varepsilon_0 - \varepsilon) = X_f \cdot \varepsilon_0 \left(1 - \frac{\varepsilon}{\varepsilon_0} \right) \quad (8)$$

$$\frac{a}{a_0} = \sqrt{\frac{\varepsilon}{\varepsilon_0}} \quad (9)$$

where ε is the void fraction of the filter bed with biomass (dimensionless), ε_0 is the initial void fraction of the filter bed with no biomass (dimensionless), a is the specific surface area of the filter bed with biomass (m^2/m^3), a_0 is the initial specific surface area of the filter bed with no biomass (m^2/m^3), and X_f is biomass density (g/m^3).

Results and Discussion

Parameters estimation and sensitivity analysis

The parameters and initial conditions in this study are either measured directly or calculated based on experimental data. The results are given in Table 2.

The toluene removal rates (r) of the four biofilters for each sampling day are listed in Fig. 1. The average toluene removal rate between two sequential sampling days was determined and used to calculate the biomass concentration during the relative period. The biomass density (X_f) was measured using the weighing method previously described and was assumed to be constant during the whole period of operation.

The value of β was estimated using the regression method, based on the removal rate and biomass data after Day 75. According to Equation (6), when t is greater than 75 d, most of the increment of total biomass is inert because the value of e^{-bt} is very small. Thus, the biomass accumulation rate is pro-

portionate to the toluene removal rate, and the slope is determined by β . The regression results show that β equals 0.2, which is similar to what has been reported by other researchers (Rittmann and McCarty, 2001). The values of Y and b are calculated based on the biomass concentration data of Biofilter #1. By changing, within reasonable ranges, the values of Y and b , Equations (6) and (7) will give different calculated total biomass concentrations. The values of Y and b are determined when the sum of the squared difference between the calculated total biomass concentration and the experimental total biomass concentration is minimized.

The initial active biomass concentration and inert biomass concentration are very small and have no significant impact on total biomass calculation result (see the sensitivity analysis in the next paragraph). Thus, the values of X_{a0} and X_{i0} are assumed to be 0.05 g/L. The initial void fraction of the filter bed is measured by filling the filter bed with a certain volume of water.

In order to estimate the impact of each parameter on the simulation results, a sensitivity analysis was performed on all the parameters by increasing each parameter by 10% while the other parameters remained unchanged. A relative sensitivity index (RSI) was defined as

$$RSI = \frac{\sum_{i=1}^n \sqrt{(X_{ti} - X_{ti0})^2}}{n \cdot 10\%} \quad (10)$$

where X_{ti} is the calculated total biomass concentration after one parameter is changed, X_{ti0} is the calculated total biomass concentration when all the parameters have the original values in Table 2, and i and n represent the serial number and total number of divisions between two sequential sampling days. According to the RSI results shown in Table 2, the toluene removal rate (r) and yield coefficient (Y) have the greatest impact on total biomass predictions when compared to other parameters, but that impact is not particularly significant because their RSI results are lower than 1.

Biomass accumulation simulation

Using the parameter estimation results, the biomass concentrations of the four biofilters during Phases I and II were calculated and compared with the experimental data. In the

TABLE 2. VALUES OF MODEL PARAMETERS AND THEIR SENSITIVITY ANALYSIS RESULT

Model parameter	Value	Unit	Estimation method	RSI
r	^a	$\text{g}/\text{m}^3/\text{h}$	Measurement	0.98
X_f	1×10^5	g/m^3	Measurement	-
β	0.2	dimensionless	Calculation based on experimental data	0.54
Y	0.7 (with inert biomass) 0.5 (without inert biomass)	$\text{g cell}/\text{g toluene}$	Calculation based on experimental data	0.98
b	0.007 (with inert biomass) 0.002 (without inert biomass)	h^{-1}	Calculation based on experimental data	0.30
X_{a0}	0.05	g/L	Assumption	0.07
X_{i0}	0.05	g/L	Assumption	0.07
ε_0	0.6	dimensionless	Measurement	-

^aThe toluene removal rates varied by time for different biofilters. The average toluene removal rate between two sampling days can be used to calculate the biomass concentration during the period.

FIG. 1. Variation of toluene removal rate for four biofilters.

microbial model, when inert biomass is considered, the calculated biomass accumulation pattern shows agreement with the experimental data for all four biofilters in Phase I and Phase II (Fig. 2). This result verifies that the microbial growth model with an inert biomass assumption successfully describes the real biomass accumulation process.

Figure 3 shows the biomass simulation results when inert biomass is ignored. For all four biofilters, the calculated total biomass concentrations without an inert biomass assumption agree fairly well with the experimental data up to Day 60 but fail to simulate the biomass variation trend after Day 60. This result indicates that microbial growth models without an inert biomass assumption may be accurate if the operating period is not very long. However, for long-term operations, inert biomass cannot be ignored in biomass accumulation simulations.

According to the microbial growth model based on the assumption of inert biomass, total biomass concentration will increase continuously after long-term operation, even if the inlet VOC loading or VOC removal rate is very small. This means that all biofilters will eventually clog without a biomass control, although the point at which they clog will vary. Thus, it is important to recognize the impact of inert biomass on the long-term performance of a biofilter.

Variation of active biomass and inert biomass concentrations

The active and inert biomass concentrations in the four biofilters were calculated according to Equations (4) and (5) and the results are shown in Fig. 4.

FIG. 2. Calculated total biomass concentrations under inert biomass assumption compared with experimental results.

FIG. 3. Calculated total biomass concentrations without inert biomass assumption compared with experimental results.

The active biomass concentrations of the four biofilters increased quickly at the beginning of the operating period and then, in response to variations in the inlet toluene concentration, changed to different levels in Phase II. The inert biomass increased throughout the operating period, and most of the increased biomass was inert biomass in Phase II. The ratios of active biomass to total biomass for the four biofilters decreased continuously during the operating period, and inert biomass was dominant in the total biomass by the end of the operating period. Some similar results were reported by Song and Kinney (2000, 2005), who found that carbon accumulation in a biofilter continued throughout the period of operation while the cell count remained relatively constant.

In addition to investigations into the ratios of active to inert biomass, there is a need for investigations of the

distribution and function of active and inert biomasses on biofilms and their impact on biofilter performance (Morgenroth and Milferstedt, 2009). According to some experimental and computational results, inert biomasses accumulate primarily near the attachment surface, while active bacteria predominate near the outer surface, because of higher concentrations of substrates and oxygen on the biofilm surface (Laspidou and Rittmann, 2004). Given this, current biomass control techniques, for example, backwashing or chemical washing, will remove much of the active biomass on the biofilm surface and result in a decline in VOC removal capacity. The ideal biomass control technique should remove most of the inert biomass and preserve as much active biomass as possible. A recent study found that a continuous injection of a certain concentration of ozone into the filter bed can lower the

FIG. 4. Variation of calculated active and inert biomass concentrations under inert biomass assumption for the four biofilters.

FIG. 5. Variation of calculated a/a_0 and $\varepsilon/\varepsilon_0$ under inert biomass assumption.

biomass growth rate and preserve the VOC removal capacity simultaneously (Wang *et al.*, 2009). This finding may lead to the creation of an ideal biomass control method.

Filter bed structure change and its impact on biofilter performance

Using Equations (8) and (9), for each biofilter, the fractions of void fraction and specific surface area to the original values were calculated, and the results are shown in Fig. 5. Both the void fractions and specific surface areas of the four biofilters decrease during the period of operation. The void fraction reduced more quickly than did the specific surface area. The

final void fraction of Biofilter #1 is only 67% of its initial level, while the final specific surface area is 82%. This result indicates that the void fraction is more sensitive to biomass accumulation than specific surface area.

The filter bed structure change will affect the VOC removal rate and pressure drop of the biofilter (Song and Kinney, 2000; Morgan-Sagastume *et al.*, 2001). Figures 1 and 6 show the variation of toluene removal rate and pressure drops in the four biofilters during the operating period. The toluene removal rates of Biofilter #1 and #2 are found to have decrease in Phase II (see Fig. 1), and the pressure drops of all four biofilters are found to rise in Phase II. Furthermore, the variations in toluene removal rate and pressure drop between the four

FIG. 6. Variation of filter bed pressure drop.

biofilters can be explained by the variation trend of specific surface areas and void fractions.

Conclusions

The following conclusions can be drawn from the results presented in this study:

1. Inert biomass accumulation cannot be ignored in microbial growth models of biofiltration process, especially in long-term performance simulations.
2. During long-term operation, the active biomass concentration reaches a constant value while the inert biomass concentration continues to increase and becomes dominant in the accumulated biomass. The final active biomass concentration and inert biomass accumulation rate both have a positive correlation with the VOC removal rate and inlet VOC loading.
3. The results of the filter bed structure simulation show that the void fraction is more sensitive to biomass accumulation than is the specific surface area.
4. An ideal biomass control technique should remove most of the inert biomass and preserve as much as possible of the active biomass.

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Author Disclosure Statement

No competing financial interests exist.

Notation

a	the specific surface area of the filter bed with biomass (m^2/m^3)
a_0	the initial specific surface area of the filter bed with no biomass (m^2/m^3)
b	the shear/decay coefficient (h^{-1})
r	the VOC removal rate ($\text{g}/[\text{m}^3 \cdot \text{h}]$)
t	time (h)
X_a	the active biomass concentration (g/m^3)
X_{a0}	the initial active biomass concentration when $t=0$ (g/m^3)
X_f	biomass density (g/m^3)
X_i	the inert biomass concentration (g/m^3)
X_{i0}	the initial inert biomass concentration when $t=0$ (g/m^3)
X_t	the total biomass concentration in the filter bed (g/m^3)
Y	the yield coefficient of active biomass ($\text{g cell}/\text{g toluene}$)
β	the ratio of produced inert biomass to lost active biomass (dimensionless)
ε	the void fraction of the filter bed with biomass (dimensionless)
ε_0	the initial void fraction of the filter bed with no biomass (dimensionless)

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