

Modeling of biomass accumulation and filter bed structure change in biofilters for gaseous toluene removal

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ABSTRACT

In this study, a proper microbial growth model was established and analyzed to investigate the biomass accumulation process in biofilters. Four biofilters treating gaseous toluene were set up in parallel and were operated under different inlet toluene loadings for 100 days. Based on the experimental data of microbial biomass and toluene removal rate, the kinetic parameters were decided by either estimation from literature or parameter regression. The calculation results based on the model showed a good agreement with the experimental data of biomass change. By applying the model, it is found that lower than 50% of biomass in the filter bed was active during the last 50 days for the four biofilters. In addition, the void fraction of the filter bed with highest loading was only 55% of the initial level at the end of the operation. All the experimental and calculation results indicated that the microbial growth model could successfully describe the biomass accumulation process and have the potential to predict the long-term performance of biofilters.

1 INTRODUCTION

Over the past two decades, biofiltration was recognized as a cost-effective method to treat volatile organic compounds (VOCs) (Leson and Winer, 1991). Many full-scale biofilters were set up and successfully used to treat different organic waste gases emitted from industrial process or waste treatment process (Swanson and Loehr, 1997). However, the VOCs removal capacity of the biofilter was often found to get lower while filter bed pressure drop get higher during long-term operation due to different reasons (Son *et al.*, 2005; Weber and Hartmans, 1996). Bed clogging caused by excess

biomass accumulation was one of the most important reasons for long-term performance decline. To predict long-term performance change and optimize the operation conditions, it is important to know the biomass accumulation pattern and its impact on filter bed structure.

Several microbial growth models were established in the literature to describe the biomass accumulation process in the filter beds of biofilters (Iliuta and Larachi, 2004; Song and Kinney, 2002). Some model considered the inert biomass production and its microbial growth pattern was quite different from those models with no inert biomass description. Furthermore, most of the studies did not monitor the biomass accumulation process and verified the model by experimental data. To decide the impact of biomass accumulation to the filter bed and biofilter performance, Alonso *et al.* (1998) compared three physical filter bed models representing the geometric structure of porous media and found that spheres and pipes model could explain the performance decline of the biofilter.

The aim of this study is to describe the microbial growth pattern by developing a proper microbial growth model considering inert biomass production and verify the model based on the experimental data. The filter bed structure change due to biomass accumulation was also analyzed by combining the microbial growth model and a physical filter bed model.

2 MATERIALS AND METHODS

2.1 EXPERIMENTAL SETUP

Four paralleled biofilters, identified as 1#, 2#, 3# and 4# respectively were build in this experiment. The diagram of the biofilter system was shown in Figure 1. The packed filter bed had a diameter of 120 mm and a height of 200 mm. Wood chips were used as the organic packing medium and propylene spheres were added into the filter bed (Xi *et al.*, 2005). The void fraction of the filter bed was 0.60 at the beginning of the operation period. A gas feeding apparatus was set up to produce a toluene gas with desired concentration and flow rate (Xi *et al.*, 2005).

2.2 OPERATION CONDITIONS

After being inoculated with activated sludge, the four biofilters were operated continuously for more than 100 days. The operating conditions during this period are shown in Table 1.

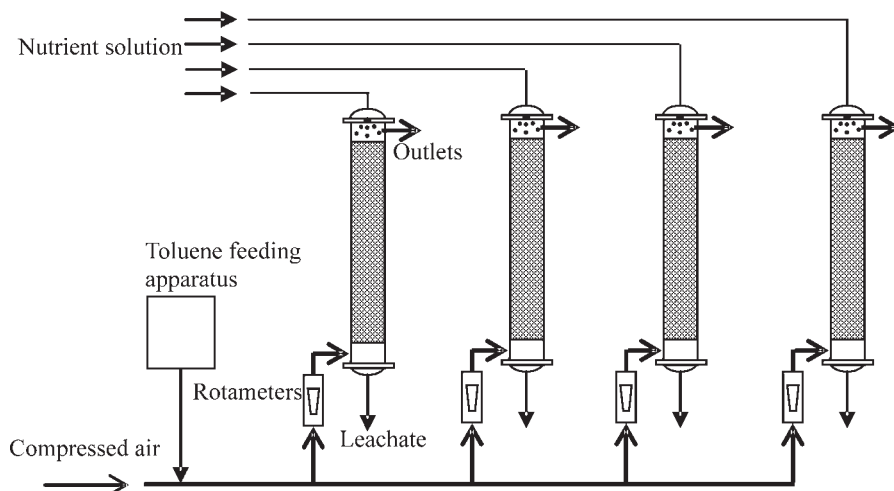


Figure 1. Diagram of the experimental system.

Table 1.
Operating conditions of the four biofilters.

Items or parameters	Value
Temperature	20~25 °C
Relative humidity	50~85
Inlet toluene concentration	0~50d: 950 mg·m ⁻³ ; 50~100d: 1#:1000mg·m ⁻³ , 2#:600mg·m ⁻³ , 3#: 270 mg·m ⁻³ , 4#:90 mg·m ⁻³
Flow direction	Upflow
Flow rate	0.3 m ³ ·h ⁻¹
Empty bed retention time	27 s
Superficial velocity	26.5 m·h ⁻¹
Spraying intervals	Once every 8 hours, 1min for each time
Quantity sprayed	9~10 L·m ⁻² ·min ⁻¹

The experimental period was divided into two phase. In Phase I (day 1~50), the inlet concentrations of the four biofilters were same and remained around 950 mg·m⁻³. In Phase II (day 51~100), the inlet toluene concentrations of the four biofilters were set to different levels as shown in Table 1.

2.3 ANALYTICAL METHODS

During the experimental period, the inlet and outlet toluene concentrations of the four biofilters were monitored by gas chromatograph (Shimadzu GC-14B, Japan) periodically to evaluate the performance of the biofilters. Weighing method was carried out to measure the amount of biomass in the filter bed (Okkerse *et al.*, 1999). The total dry biomass concentration in the filter bed could be calculated by following equation (1).

$$X_t = \frac{(W_t - W_r - W_p)(1 - h)}{V} \quad (1)$$

where X_t is the biomass concentration in the filter bed, g/m^3 ; W_f is the weight of the wet biofilm on the surface of the packing media, g; W_t is the total weight of the biofilter column, g; W_r is the weight of the empty column, g; W_p is the weight of the wet packing media, g; h is the moisture content of the biofilm, dimensionless; V is the volume of the filter bed, m^3 ; Assuming that the values of W_r , W_p and h were constant during the experimental period, the value of X can be calculated by measuring W_t .

3 MODEL DEVELOPMENT

3.1 MICROBIAL GROWTH MODEL

Assuming that the dry biomass in the filter bed is consisted of active biomass and inert biomass. Thus the dry biomass concentration X_t could be expressed by the following equation:

$$X_t = X_a + X_i \quad (2)$$

where X_a is the concentration of active biomass, $\text{g}\cdot\text{m}^{-3}$; X_i is the concentration of the inert biomass, $\text{g}\cdot\text{m}^{-3}$. The variation of X_a and X_i could be expressed as:

$$\frac{dX_a}{dt} = Y(-r) - bX_a \quad (3)$$

$$\frac{dX_i}{dt} = \beta bX_a \quad (4)$$

where Y is the yield coefficient of active biomass, dimensionless; $-r$ is VOCs removal rate, $\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$; b is shear/decay coefficient, h^{-1} ; β is the ratio of produced inert biomass to lost active biomass, dimensionless; t is time, h. Assuming that Y , b , β is constant for the microbial community in the filter bed and $-r$ is constant with constant operation conditions under pseudo-steady state, the following equations could be drawn:

$$X_a = (X_{a0} - \frac{Y(-r)}{b})e^{-bt} + \frac{Y(-r)}{b} \quad (5)$$

$$X_i = \beta(\frac{Y(-r)}{b} - X_{a0})e^{-bt} + \beta Y(-r)t + \beta X_{a0} + X_{i0} - \beta \frac{Y(-r)}{b} \quad (6)$$

$$X_t = (X_{a0} - \frac{Y(-r)}{b})(1 - \beta)e^{-bt} + \beta Y(-r)t + \beta X_{a0} + X_{i0} + (1 - \beta) \frac{Y(-r)}{b} \quad (7)$$

Where X_{a0} is the initial active biomass concentration when $t=0$, $\text{g}\cdot\text{m}^{-3}$; X_{i0} is the initial inert biomass concentration when $t=0$, $\text{g}\cdot\text{m}^{-3}$.

3.2 FILTER BED STRUCTURE MODEL

The physical filter bed model is similar with the pipes model in the literature (Alonso and Suidan, 1998). Assuming that the biofilm density is constant during microbial growth, the total biomass concentration X_t could be expressed as:

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

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

Where ε_0 is the initial void fraction of the filter bed with no biomass, dimensionless; ε is the void fraction of the filter bed with biomass, dimensionless; a_0 is the initial specific surface area of the filter bed with no biomass, $\text{m}^2\cdot\text{m}^{-3}$; a is the specific surface area of the filter bed with biomass, $\text{m}^2\cdot\text{m}^{-3}$; X_f is the biomass density, $\text{g}\cdot\text{m}^{-3}$.

4 RESULTS AND DISCUSSION

4.1 Model parameter estimation

To describe the microbial growth process, the value of X_{a0} , X_{i0} , Y , $-r$, b and β should be estimated by either experiment result or referring to literature. The values of these model parameters were listed in Table 2.

Table 2.
Values of model parameters

Model parameter	value	unit	Estimation method
X_{a0} (initial active biomass concentration)	0	$\text{g}\cdot\text{m}^{-3}$	Assumption
X_{i0} (initial inert biomass concentration)	0	$\text{g}\cdot\text{m}^{-3}$	Assumption
Y (yield coefficient)	0.6	dimensionless	From literature (Rittmann, B.E. and McCarty, P.L. 2001)
$-r$ (VOCs removal rate)	*	$\text{g}\cdot\text{m}^{-3}\cdot\text{h}^{-1}$	Averaged by experimental data
β (ratio of produced inert biomass to lost active biomass)	0.2	dimensionless	regression from the experimental data ($R^2=0.96$)
b (shear/decay coefficient)	0.005	h^{-1}	regression from the experimental data ($R^2=0.96$)

* The average toluene removal rates were different in different phase for the four biofilters.

4.2 MODEL SIMULATION AND VALIDATION

With the parameters, the biomass concentrations of the four biofilters during the operation period were calculated and compared with the experimental data. The results was shown in Figure 2. The results demonstrated that the microbial growth pattern of the biofilter could be well simulated by the microbial growth model established in this study.

By the microbial growth model (equation 5, 6), the active and inert biomass concentrations in the filter bed were also calculated. The results were show in Figure 3. The results demonstrated that lower than 50% of biomass in the filter bed was active during the last 50 days of operation. Okkerse *et al.* (1999) and Song *et al.* (2002) also established microbial growth model for biofilter or biotrickling filter considering inert biomass production, their work did not show much experimental data. The result in this study verified that the inert biomass could not be omitted and most of the accumulated biomass was inert biomass after long time operation.

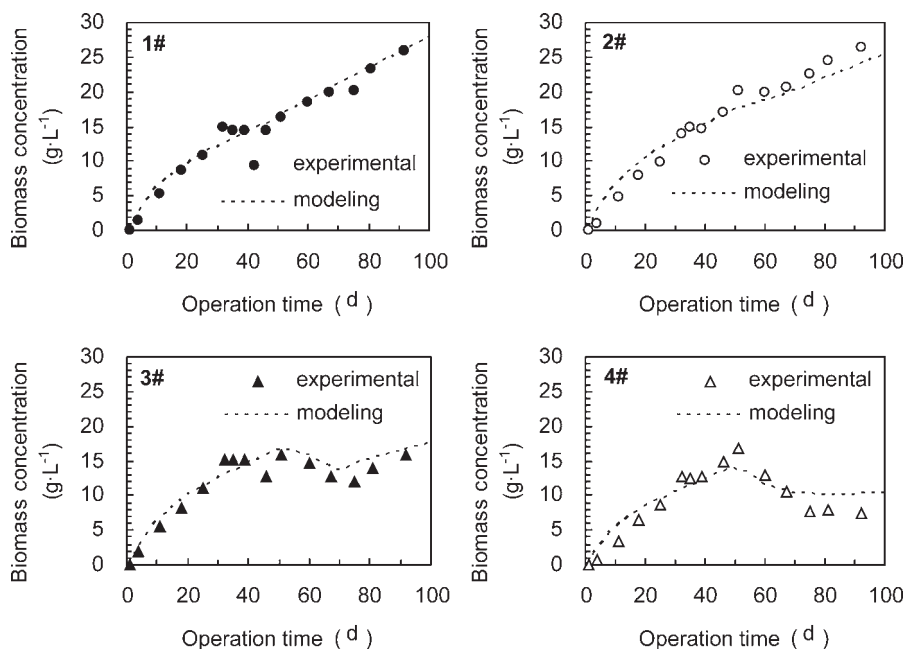


Figure 2. Variations of the predicted and experimental biomass concentration.

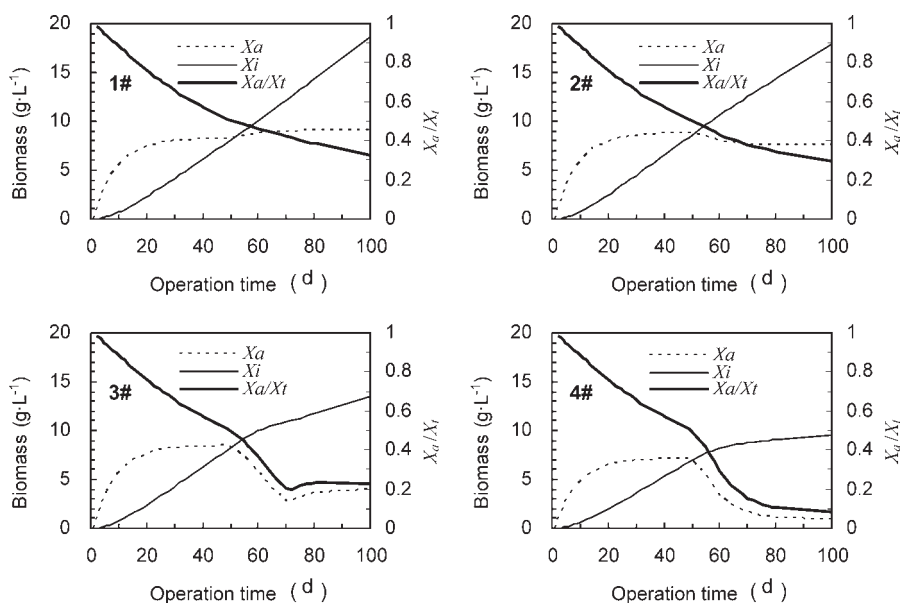


Figure 3. Variation of the active and inert biomass concentration of the four biofilters.

4.3 FILTER BED STRUCTURE CHANGE

Based on the filter bed structure model (Equations 8, 9), the characteristic parameters (ε and a) of the filter bed could be calculated. The value of X_f and ε_0 was measured and the results were $1 \times 10^5 \text{ g} \cdot \text{m}^{-3}$ and 0.6 respectively. The calculated void fraction and specific surface area during the operation period were shown in Figure 4.

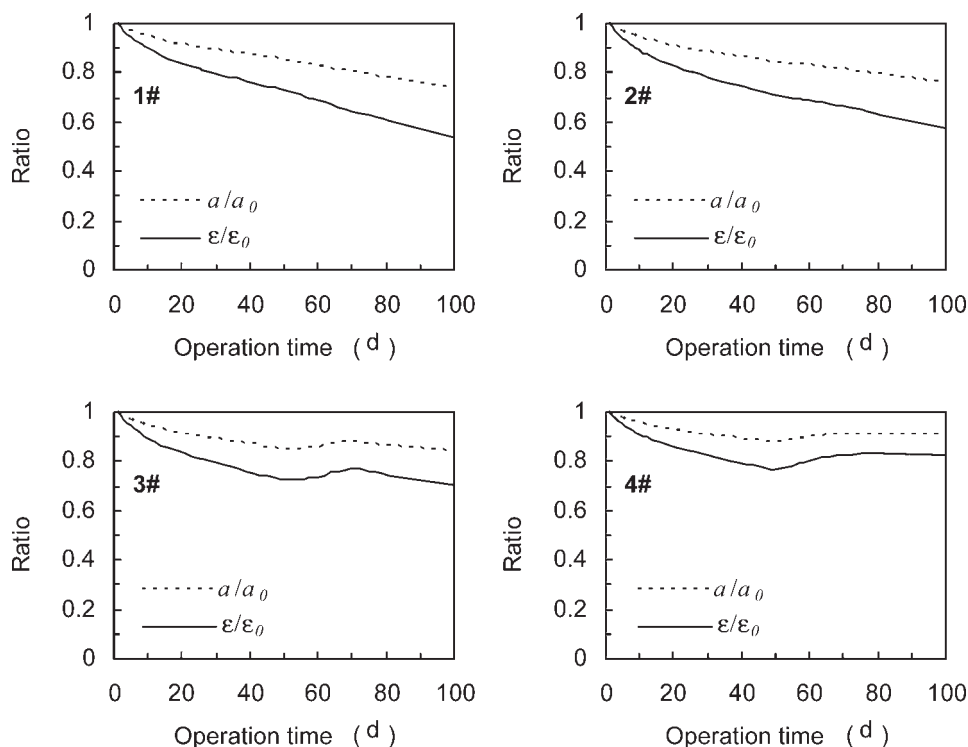


Figure 4. Variation of a/a_0 and $\varepsilon/\varepsilon_0$ during the operation period.

The void fraction and the specific surface area of the filter bed can affect the VOCs removal capacity and bed pressure drop of the biofilter (Morgan-Sagastume *et al.*, 2001; Song and Kinney, 2000). The results in Figure 4 illustrated that the void fraction and the specific surface area of the filter bed would be lowered after the excess biomass accumulated. For biofilter 1#, the void fraction was only 55% of the initial level at the end of the operation.

5 CONCLUSIONS

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

- (1) The microbial growth model could successfully describe the biomass accumulation process under different operation conditions.
- (2) After long time operation, the accumulated biomass in the filter bed was mainly inert biomass and the ratio of inert biomass would raise continuously.
- (3) The filter bed structure model could quantitatively determine the void fraction and specific surface area of the filter bed decrease due to excess biomass accumulation.

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