Int. J. Environ. Sci. Tech.
Vol. 2, No. 1, pp. 69-82, Spring 2005

Simulation of biofilter used for removal of air contaminants (ethanol)

[1]M. Ardjmand, [2]A. Safekordi and [3*]S. Farjadfard

[1]Department of Chemical Engineering, Islamic Azad University, Tehran South Branch, Tehran, Iran

[2]Department of Chemical Engineering, Sharif University of Technology, Tehran, Iran

[3]Department of Environmental Engineering, Islamic Azad University, Science and Research Campus, Tehran, Iran

Abstract

Mathematic modeling and simulation of a biofilter system was developed for biofilters filled by three different packing materials such as granular activated carbon (GAC), compost mixed with diatomaceous earth (DE), and compost, respectively, and the effects of biofilter length, packing material, biological activity and the operation time of system on the removal of ethanol (influent contaminant) were studied. The mathematical model for analysis of mass transport phenomena in the biofilter was solved using a two-step, explicit finite difference approximation technique and computer simulation was carried out. The obtained results show that at the early stage of biofiltration the dominant mechanism is adsorption and after saturation of packing by contaminant, biological processes became the dominant mechanism. GAC packed biofilter needs more time to reach to steady state in comparison to the two other packing. GAC is the best adsorbent for contaminant removal; however, compost provides a better environment for microbial growth and activity. The proposed procedure is applicable to analyze the behavior of a biofiltration system used in removal of volatile organic compounds.

Key words: *Simulation, biofilter, ethanol, removal*

**Corresponding Author, E-mail:simafarjadfard@yahoo.com*

Introduction

Volatile organic compounds (VOCs) are liquids or solids that contain organic carbon which is vaporized at significant rates (de Nevers, 2000), if they left untreated can pose potential health risks in addition to causing severe environmental problems. A novel technology for treatment of gases is biofiltration (Zarook, *et al.*, 1996). Biofiltration can offer a number of advantages when compared to other air pollution control technologies like absorption, adsorption, catalytic oxidation, incineration, ozonization, chlorination, and chemical scrubbing; it has become one of the leading technologies for controlling VOC emissions (Spigno, *et al.*, 2003; Zarook, *et al.*, 1998; and Zarook, *et al.*, 1997). Biofiltration is a cost effective and reliable option for treating off-gas streams that have large flow rates and low concentrations of odors, VOCs, or hazardous air pollutants (Dehghanzadeh, *et al.*, 2005; Schwarz, *et al.*, 2001; and Deshusses, 1997). In biofiltration, organic contaminants are degraded by aerobic heterotrophic microbial species. The polluted air stream is passed through the biofiltration column and flows through the packing material of the filter bed (up flow or down flow). The microbial population is immobilized on the surface of the packing material where they form an active biofilm layer. Because of the concentration gradient between the two phases, the contaminant diffuses from the gas phase into the liquid biofilm and is then biodegraded by the microorganisms present in the liquid biolayer (metabolite formation is then possible across the column). These microorganisms ensure their growth and survival using the carbon source from the organic pollutant and the nutrients available in the packing material (Elmrini, *et al.*, 2004). If the residence time and the size of the biofilter are large enough then the existing stream will be pollutant-free air (Zarook and Shaikh, 1996).

A typical biofilter configuration is shown in Figure 1. The contaminated off-gas is passed through a preconditioner for particulate removal and humidification (if necessary). The conditioned gas stream is then sent into the bottom of a filter bed of soil, peat, composted organic material (such as wood or lawn waste), activated carbon, ceramic or plastic packing, or other inert or semi-inert media. The media provides a surface for microorganism attachment and growth. The off-gas stream is typically either forced or included through the system with a blower. A vent stack is employed when necessary to meet monitoring or discharge requirements (Adler, 2001). The particular contaminants of interest must be water

soluble, biodegradable and nontoxic for biofiltration (e.g. ethanol, methanol). Beside organic compounds, inorganic compounds such as hydrogen sulfide and ammonia are also biodegraded well (Miller and Allen, 2004; Devinny, *et al.*, 1999; and Swanson and Loehr, 1997). Several experimental studies were carried out to show that the removal of VOCs (Kennes and Veiga, 2004; Deshusses and Johnson, 2000; Neal and Loehr, 2000; and Mohseni and Allen, 2000), hydrogen sulfide (Busca and Pistarino, 2003; Cook, *et al.*, 1999; Chitwood and Devinny, 1999; Shojaosadati and Elyasi, 1999; Yang and Allen, 1994; and Chung, *et al.*, 1997), and ammonia (Hong and Park, 2005; Martin, *et al.*, 1996; Heslinga and Van Groenestijn, 1997; and Chung, *et al.*, 1997) in biofilter is feasible. However, to analyze physical, chemical and biochemical phenomena occurring on biofiltration process and subsequently developing it into an optimized technology in waste treatment engineering, precise modeling of the process is required. Analysis of biofiltration and its modeling is rather limited due to complex nature of the process.

The earlier model was developed for removal of a single contaminant in a submerged biological filter by Jenning (1976). The model was then followed by Ottengraf and Van den Oever (1983). In this model, the ability of biofilters for removal of VOCs from air was described for the first time. The recent research include: Ottengraf (1986), Tiwaree, *et al.* (1992), Shareefdeen, *et al.* (1993), Shareefdeen and Baltiz (1994), Ergas, *et al.* (1994), Yang and Allen (1994), Hodge and Devinny (1994, 1995), Morgenroth, *et al.* (1995), Deshusses, et al. (1995a, 1995b, 1996), Tang, et al. (1996), Abumaizar, et al. (1997), Baltzis, *et al.* (1997), Hwang, *et al.* (1997), Zarook, *et al.* (1993, 1997, 1998), Alonso, *et al.* (1997, 1998), Okkerse, *et al.* (1999), and Amanullah, *et al.* (1999) models. These models differ mainly in the following aspects: (1) model for fluid flow, (2) model for biodegradation reaction in the biofilm, (3) details of interphase transport, and (4) role of the support media (Amanullah, *et al.*, 1999).

In the present study the treatment of ethanol vapors and its removal from air by biofiltration was mathematically simulated. The model of Hodge and Devinny (1995, 1997) was been chosen to study the biofiltration of air contaminated by ethanol vapor and the results were used to analyze the treatment process.

Materials and Methods

Mathematical Model

Hodge and Devinny's model (1995, 1997) describes basic transport and biological processes occurring in biofiltration. As air passes through the filter, its contaminant concentration is affected by advection, dispersion, adsorption, absorption, and biological processes (Figure 2). Two-phase system was assumed: the air phase (phase 1) and the water-solid phase (phase 2).The model describes the

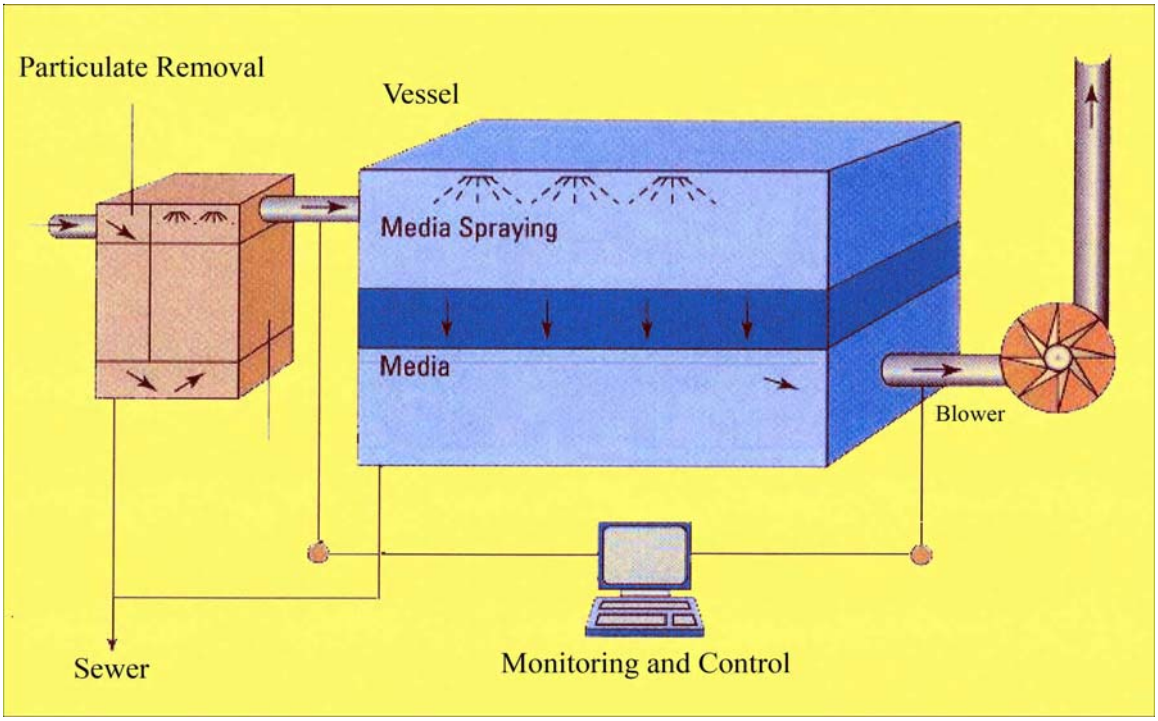

Figure 1: Typical biofilter configuration (Adler, 2001)

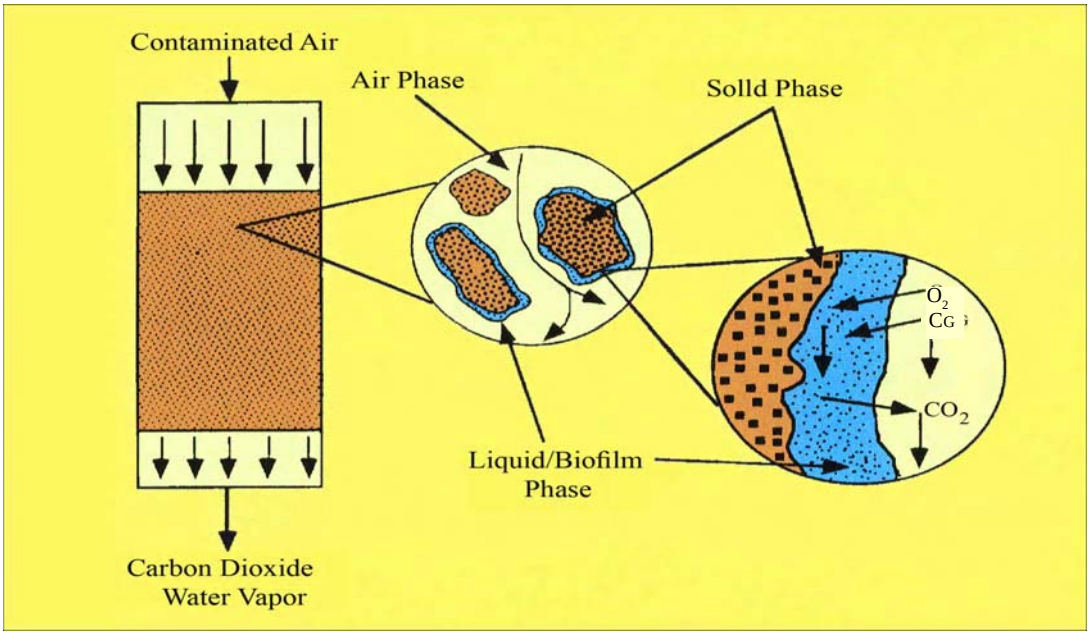

Figure 2: Internal mechanisms of a biofilter. Contaminated air (C_G) passes through the filter bed medium (compost, peat, soil, etc.) with oxygen and sorbs into a microbial biofilm/liquid phase attached to the filter medium. Microbes convert contaminant to carbon dioxide and water (Devinny, et al., 1999).

evolution of carbon dioxide by microorganisms and predicted concentration profiles in the filter. The effects of contaminant adsorption and biological degradation processes are separately considered in this model. As a result, the model delineates which process is dominant at different modes of operation.

In order to formulate a feasible mathematical model of biofiltration, several simplifying assumptions have to be made. The assumptions of the model are as follows:

1-No large-scale turbulence occurs.

2-Filter material composition is homogeneous (e.g., porosity, water content, and water/biolayer thickness).

3-Biomass distribution and density are assumed to be homogenous. Adsorption is reversible.

4-Advection and diffusion of adsorbate in the water/ biolayer are negligible. Rate of the substrate consumption by microorganisms follows first-order kinetics.

5-Carbon dioxide production follows the stoichiometric relationship

$$C_2H_5OH + 3\,O_2 \longrightarrow 2\,CO_2 + 3\,H_2O \qquad (1)$$

6- Initial CO_2 concentration in biofilter is zero.

It is also assumed that large turbulence is negligible according to experimental data which shows laminar flow pattern (0.2 < Reynolds No. < 0.5, for full-scale operations) in typical biofilters (Leson and Winer, 1991).

The transport and biological processes together form a set of partial differential equations providing a complete description of a constituent concentration in both phases. These equations are:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - \left(\frac{1-\theta}{\theta}\right)\left[k(k_h C - C_{ads})\right] \qquad (2)$$

$$\frac{\partial C_{ads}}{\partial t} = k(k_h C - C_{ads}) - b\,C_{ads} \qquad (3)$$

$$\frac{\partial [CO_2]_{ads}}{\partial t} = k_c(k_{hc}[CO_2] - [CO_2]_{ads}) + R_c(b\,C_{ads}) \qquad (4)$$

Specific solution for model equations

The differential equations can be simplified to describe steady-state conditions for a biofilter. The solutions were used to determine constants and for comparison with numerical solutions. Under steady-state conditions (constant input concentrations and adsorptive equilibrium), contaminant removal will occur as a result of biological degradation, only. Combining equation 2 and equation 3 yields (Hodge and Devinny, 1995):

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - \left(\frac{1-\theta}{\theta}\right)\left(\frac{\partial C_{ads}}{\partial t} + b\,C_{ads}\right) \qquad (5)$$

At equilibrium, the concentrations in the air and solids/water phases are proportional:

$$C_{ads} = k_h C \quad (6)$$

So

$$\frac{\partial C_{ads}}{\partial t} = k_h \frac{\partial C}{\partial t} \quad (7)$$

and Eq. (5) becomes:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - (\frac{1-\theta}{\theta})(k_h \frac{\partial C}{\partial t} + b\, k_h C) \quad (8)$$

The ratio of the masses of contaminant in the two phases is:

$$k_m = \frac{M_{ads}}{M_{air}} = \frac{C_{ads}(1-\theta)}{C\theta} = k_h(\frac{1-\theta}{\theta}) \quad (9)$$

Then Eq. (8) becomes:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - k_m \frac{\partial C}{\partial t} - b\, k_m C \quad (10)$$

It is useful to define a "retardation factor" analogous to that used to predict movement of contaminants in ground water. Retardation factor, R, is defined by equation 11:

$$R = \frac{M_{ads} + M_{air}}{M_{air}} = 1 + k_m \quad (11)$$

From Eq. (10):

$$(1+k_m)\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} - V\frac{\partial C}{\partial x} - b_1 k_m C \quad (12)$$

Substituting Eq. (11) in Eq. (12), gives:

$$\frac{\partial C}{\partial t} = \frac{D}{R}\frac{\partial^2 C}{\partial x^2} - \frac{V}{R}\frac{\partial C}{\partial x} - \frac{b_1 k_m}{R} C \quad (13)$$

The model equations [Eq. (2) to (4)] are solved using a two-step, explicit, finite difference approximation technique. In this procedure, advection is performed for one time step, then, dispersion and other processes are modeled. This method needs the condition of $V\Delta t = \Delta x$, which is less restrictive than the other techniques developed (Dresnack and Dobbins, 1968).

The entering contaminant is ethanol which is removed by biofilter. Ethanol is oxidized to carbon dioxide and water by microbial process. GAC, compost/DE and compost, are chosen as filter media, respectively. Input parameters for running computer program are initial and influent concentrations of ethanol and CO_2 in filter, biofilter packing characteristics, and biofilter operating conditions (including porosity, dispersion coefficient (ethanol-air and CO_2 –air), partition constant (ethanol in water/air and CO_2 in water/air), transfer rate constant of ethanol and CO_2, first order biodegradation rate constant, weight of CO_2 evolved per weight of degraded ethanol, length of filter, inlet area of biofilter, influent flow rate, interstitial velocity, distance step and time step) which are given in Table 1. The results are obtained in different conditions including: different lengths of biofilter, various packing types, different biological activity levels of the bed and different values of operation time.

Results

Ethanol and CO_2 concentration profiles (operating time aspects)

Concentration profiles of ethanol and the effect of biofilter length on those profiles are presented in Figures 3 and 5. Both biofilters are filled by GAC and have the same value of biological degradation rate constant (b=0.0035 h^{-1}). As ethanol moves through biofilter, it is adsorbed by packing material and ethanol biodegradation by packing microorganism occurs and CO_2 is produced as the result of ethanol degradation. As it is shown in Figure 3 and 5 the more the decrease in ethanol concentration will result the more increase in CO_2 concentration. The concentration of ethanol in the longer biofilter (L=150 cm.) effluent is less than that of shorter one (L=90 cm.), i.e., increasing the filter length causes to increase the residence time for a given flow rate and hence the mass transfer rate into the biofilm will increase. Therefore, there is a direct relation between the length and contaminant removal efficiency of a biofilter. That is more CO_2 production for longer biofilter due to its more degradation rate of ethanol. For the first day of operation, ethanol concentration levels in biofilter effluent stream air mainly controlled by packing (GAC) adsorption capacity. So, the difference between influent and effluent concentrations of ethanol is at highest level for the first day of operation.

However, for 8-th and 20-th days of operation, ethanol concentration levels in output stream are increased as a result of biological removal of

Table 1: The values of input parameters used in simulation (Devinny, et al., 1995)

Parameter	Notation	Unit	GAC	Compost/DE	Compost
Filter material:					
Porosity	θ	%	25	45	45
Alkalinity	TA	eq/l	0.0005	0.0125	0.0225
Total carbonate	Ct	moles/l	0.0005	0.0157	0.0251
pH	-	-	8.5	8	7.5
Surface loading		m/hr	23.7	23.7	23.7
Influent concentration:					
Ethanol	C	µg/l	11300	11300	11300
CO_2	$[CO_2]$	µg/l	621	621	621
Initial air-phase concentration in biofilter:					
Ethanol	-	µg/l	0	0	0
CO_2	-	µg/l	0	0	0
Air-phase dispersion coefficient:					
Ethanol	D	cm^2/h	1900	1200	1200
CO_2	Dc	cm^2/h	1900	1200	1200
Transfer rate coefficient:					
Ethanol	k	h^{-1}	0.06	0.06	0.06
CO_2	kc	h^{-1}	1000	1000	1000
Partition coefficient:					
Ethanol/filter material	kh	-	8900	4900	3700
CO_2/filter material	$k$hc	-	0.71	0.71	0.71
Biological degradation rate constant	b	h^{-1}	0.0035	0.0055	0.0061
CO_2 evolution-rate constant	CDR	-	1.91	1.91	1.91
Inlet area of biofilter	-	cm^2	45.6	45.6	45.6
Influent flow rate	-	cm^3/hr	108000	108000	108000
Distance step	∂ x	cm	5	5	5

Table 2: Comparison of the simulation results for GAC packed biofilter

Parameter	L=90 cm. biofilter	L=150 cm. biofilter
Influent ethanol concentration (µg/l)	11300	11300
Influent CO_2 concentration (µg/l)	621	621
Effluent ethanol concentration (µg/l):		
1-st day	1.78	0.000097
8-th day	1911.2	92.3
20-th day	4849.9	2317.4
Effluent CO_2 concentration (µg/l):		
1-st day	18882.1	76106.6
8-th day	53891.7	219066.3
20-th day	58264.3	244766.7
Ethanol removal efficiency (%):		
1-st day	99.98	≈100
8-th day	83.3	99.2
20-th day	57.1	79.5

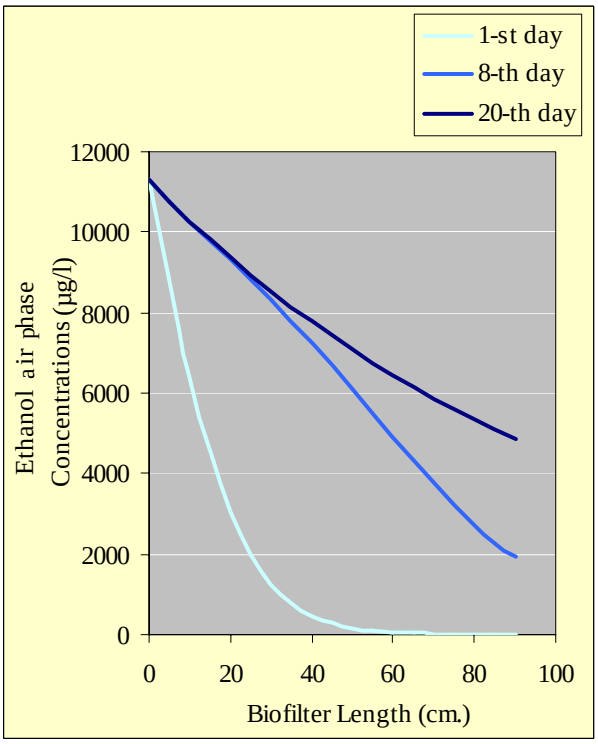

Figure 3: Ethanol concentration profiles as a function of biofilter length at different operating times
(L=90 cm., GAC packed biofilter, b=0.0035 h^{-1})

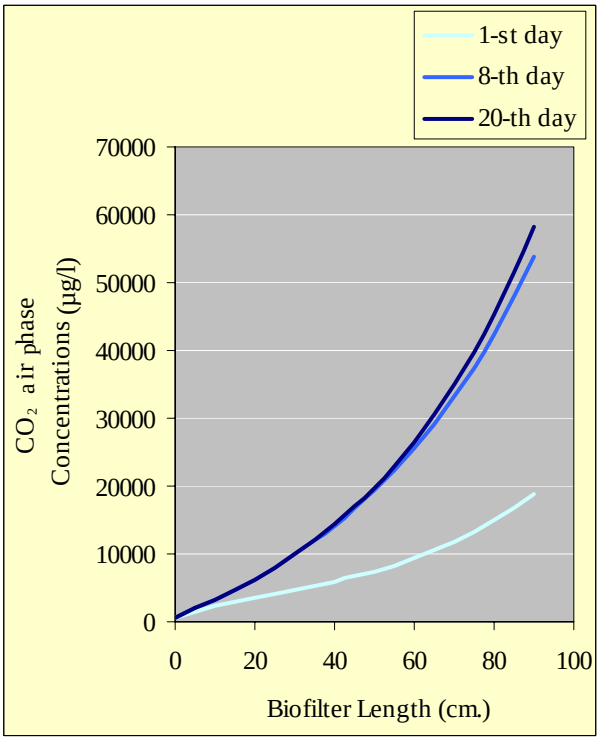

Figure 4: CO_2 concentration profiles as a function of biofilter length at different operating times
(L=90 cm., GAC packed biofilter, b=0.0035 h^{-1})

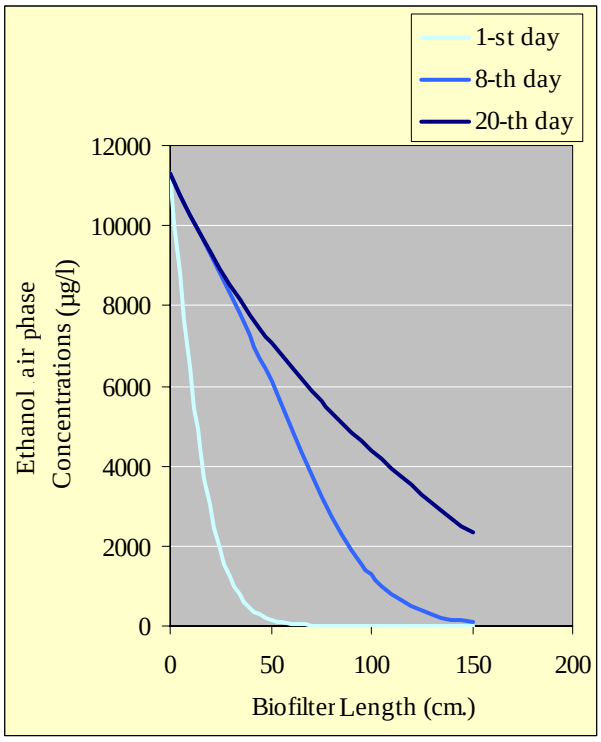

Figure 5: Ethanol concentration profiles as a function of biofilter length at different operating times
(L=150 cm., GAC packed biofilter, b=0.0035 h^{-1})

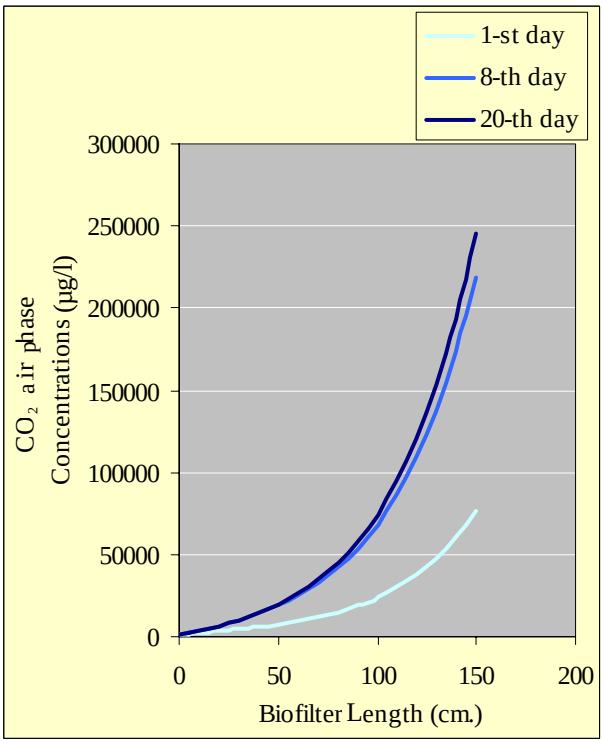

Figure 6: CO_2 concentration profiles as a function of biofilter length at different operating times
(L=150 cm., GAC packed biofilter, b=0.0035 h^{-1})

contaminants which is the dominant mechanism. CO_2 production rate is increased by time (Figures 4 and 6). During the early days of operation, a small quantity of CO_2 is produced as contaminants are removed by adsorption; however, for next period of time when the dominant mechanism shifts to the biodegradation of contaminants and packing materials are saturated, C_2H_5OH degradation occurs (Eq. (1)) and as a result CO_2 production rate is increased (Table 2).

Ethanol and CO_2 concentration profiles (biological activity aspects)

Ethanol concentration profiles are shown in Figures 7, 9 and 11 as a function of biofilter length. The results were obtained for two different conditions; (i) when there is no biological activity or viable microorganism in the system (b=0) and (ii) when the first-order biological reaction occurring in the biofilter. Biological reactions have specific role in ethanol degradation and hence ethanol concentration in effluent stream will be much lower for non zero levels of parameter b than that of b=0. However, for $b \neq 0$, in addition to adsorption mechanism, biodegradation of contaminants occur, as well.

Concentration profiles of CO_2 as a function of biofilter length are shown in Figures 8, 10 and 12 for two distinctive cases: b=0 and $b \neq 0$, respectively.

Table 3: Comparison of the simulation results for L=90 cm biofilters (20-th day of operation)

Parameter	GAC	Compost/DE	Compost
Influent ethanol concentration (µg/l)	11300	11300	11300
Influent CO_2 concentration (µg/l)	621	621	621
Effluent ethanol concentration (µg/l):			
b=0	11100.4	11299.8	11300
$b \neq 0$	4849.9	6740.6	7359.3
Effluent CO_2 concentration (µg/l):			
b=0	5049.7	6428.5	6428.5
$b \neq 0$	58264.3	52441.7	45614
Ethanol removal efficiency (%):			
b=0	1.77	≈ 0	0
$b \neq 0$	57.1	40.3	34.9

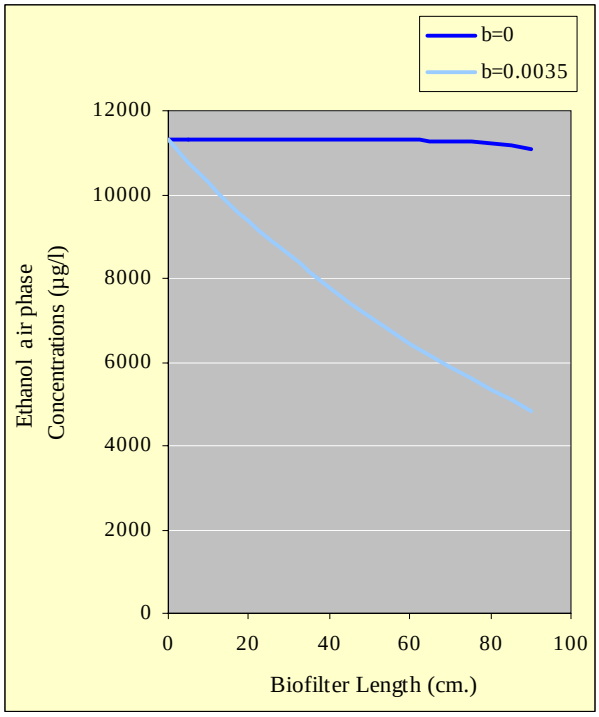

Figure 7: Ethanol concentration profiles as a function of biofilter length for biologically active and inactive systems (L=90 cm., GAC packed biofilter)

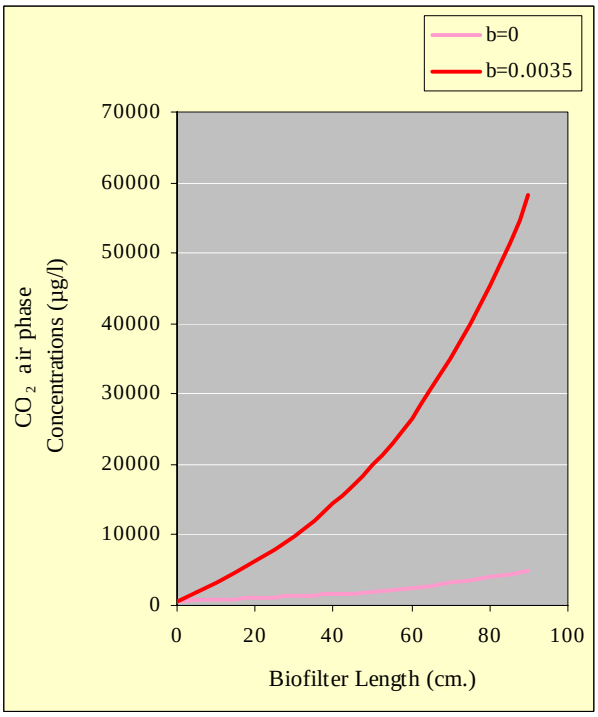

Figure 8: CO_2 concentration profiles as a function of biofilter length for biologically active and inactive systems (L=90 cm., GAC packed biofilter)

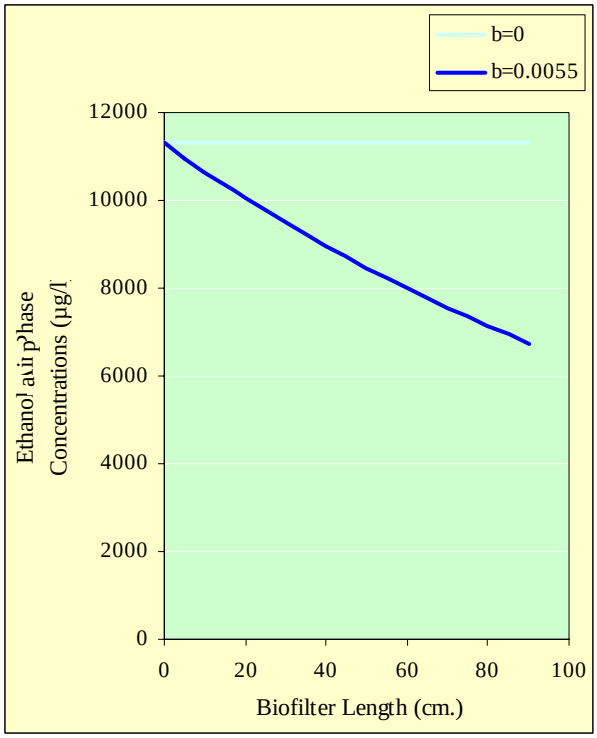

Figure 9: Ethanol concentration profiles as a function of biofilter length for biologically active and inactive systems
(L=90 cm., compost/diatomaceous-earth packed biofilter)

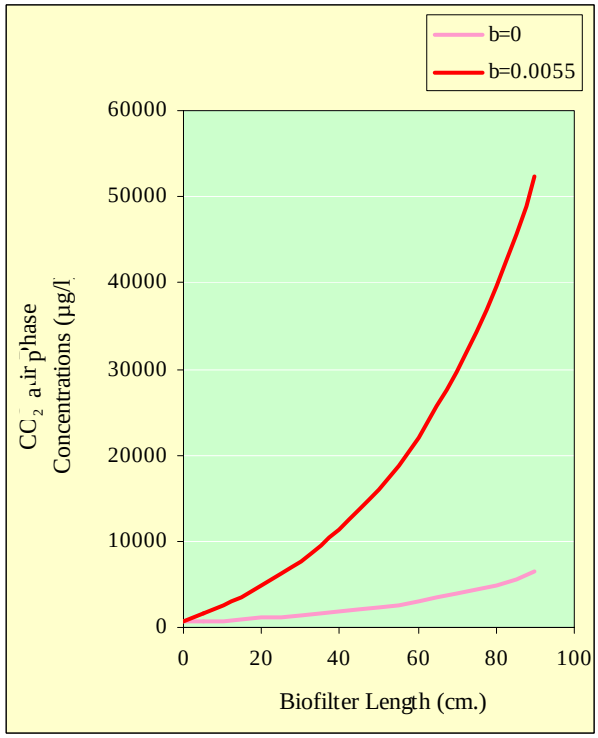

Figure 10: CO_2 concentration profiles as a function of biofilter length for biologically active and inactive systems
(L=90 cm., compost/diatomaceous-earth packed biofilter)

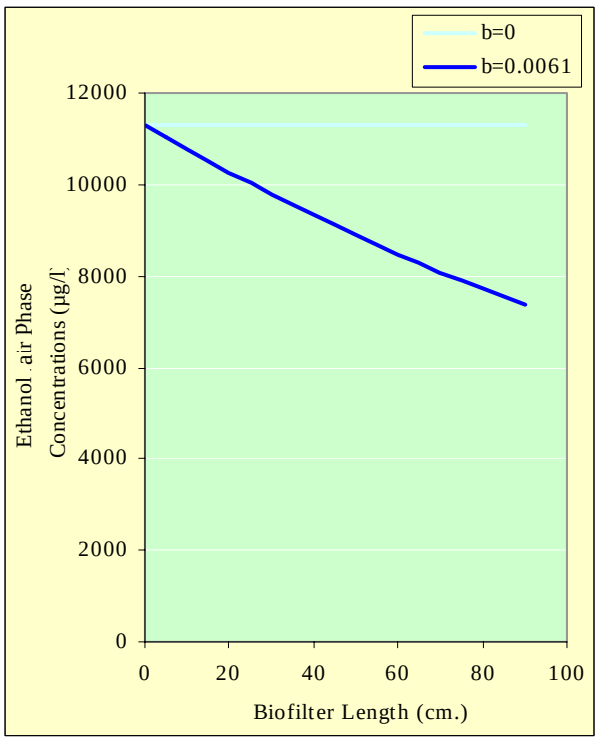

Figure 11: Ethanol concentration profiles as a function of biofilter length for biologically active and inactive systems
(L=90 cm., compost packed biofilter)

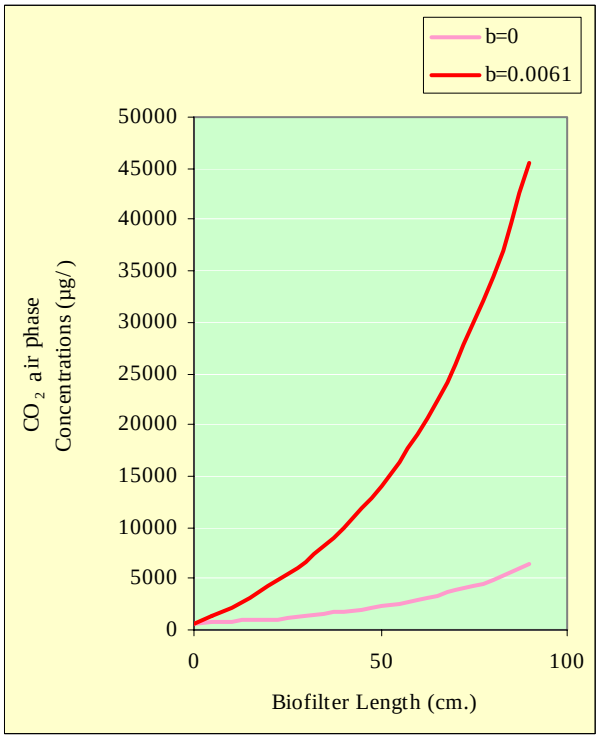

Figure 12: CO_2 concentration profiles as a function of biofilter length for biologically active and inactive systems
(L=90 cm., compost packed biofilter)

For $b \neq 0$, ethanol is degraded at the presence of microorganisms in accordance to equation 1 and CO_2 is produced as a result. The total CO_2 production is the sum of CO_2 produced by both ethanol oxidation and carbonate decomposition.
There is no oxidation of ethanol for b=0, i.e., when no biological activity exists in the system. For such a case the total CO_2 is produced by carbonate decomposition, only (Table 3).

Ethanol concentration profiles are shown in Figures 15, 16 and 17 as a function of operation time for two distinctive conditions: b=0 and $b \neq 0$. The results are obtained for three packing materials, respectively, and the biofilter length is the same for all three cases (L=90 cm.). At the beginning of biofiltration, t=0, the effluent concentration of contaminants are equal to zero where the dominant mechanism is adsorption. However, after passing an adaptation phase, biofilter saturation happens and a stable pollutant removal capacity is reached. The period of adaptation phase is directly depends on both contaminant type and environmental conditions, such as packing material type, and biofilter length. The effluent concentration is increased by increasing the rate of adsorption and the process is continued to the time of biofilter saturation where the dominant mechanism is biological removal of contaminants. The removal efficiency for biologically active biofilter ($b \neq 0$) is more than that of a filter working by adsorption (b=0). The values of different parameters are given in Table 4 for different biofiltration systems.

Ethanol concentration profile as a function of operation time (Effect of biofilter length)

Ethanol concentration profiles are shown in Figure 18, as a function of GAC packed biofilter length. Ethanol degradation is greater for longer biofilter (L=250 cm.). The longer one needs more time to reach to the steady state condition due to the more content of both packing material and microorganism and resulting in greater contaminants removal efficiency in comparison to the shorter column (L=90 cm.). The resulting parameters are given in Table 5.

Discussion and Conclusion

1. Biofilter length directly affects the contaminants removal efficiency and is of the main concern in biofilter design. However, increasing the length of biofilter results in more pressure drop and fouling of the filter. In such a condition the washing of biofilter became more difficult, as well. Hence, there is an optimum length of biofilter which eliminate the over mentioned problems and yields a proper contaminant removal efficiency.
2. CO_2 and contaminant concentration profiles can be used as a measure of biofilter performance.
3. At the stages of biofiltration, the effluent concentration of ethanol is in low level and hence the biofilter efficiency is at maximum level.
4. As biofiltration proceeds, the effluent concentration of ethanol is increased and the biofilter

Table 4: Comparison of the simulation results for L=90 cm. steady-state biofiltration

Parameter	GAC	Compost/DE	Compost
Influent ethanol concentration (µg/l)	11300	11300	11300
Time to reach to steady state	20	16	8
Effluent ethanol concentration at steady state (µg/l):			
b=0	11100.4	11296.1	11018.9
$b \neq 0$	4849.9	6740.2	7290.3
Ethanol removal efficiency (%):			
b=0	1.77	0.03	2.49
$b \neq 0$	57.1	40.4	35.5

Table 5: Comparison of the simulation results for GAC packed biofilter (20-th. day of operation)

Parameter	L=90 cm. biofilter	L=150 cm. biofilter	L=250 cm. biofilter
Influent ethanol concentration (µg/l)	11300	11300	11300
Effluent ethanol concentration (µg/l)	4849.9	2317.4	163.2
Ethanol removal efficiency (%)	57.1	79.5	98.6

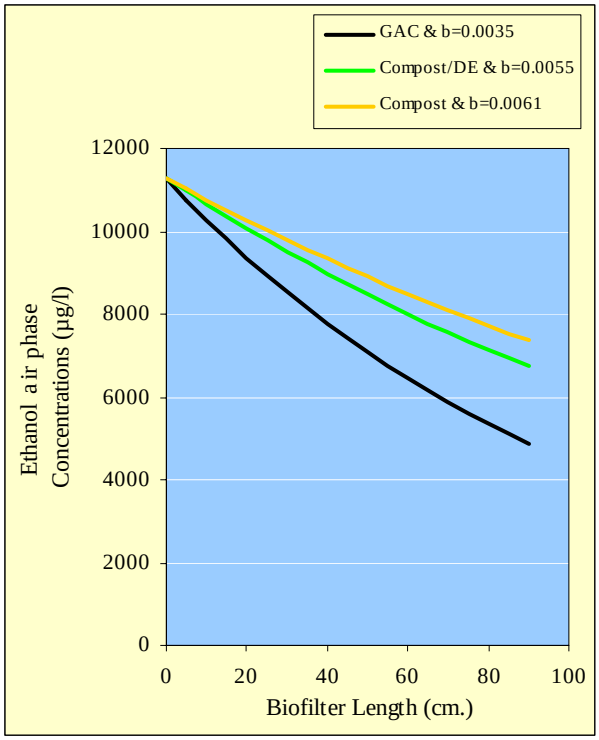

Figure 13: Ethanol concentration profile as a function biofilter length for three different packing materials
(L=90 cm., b ≠ 0)

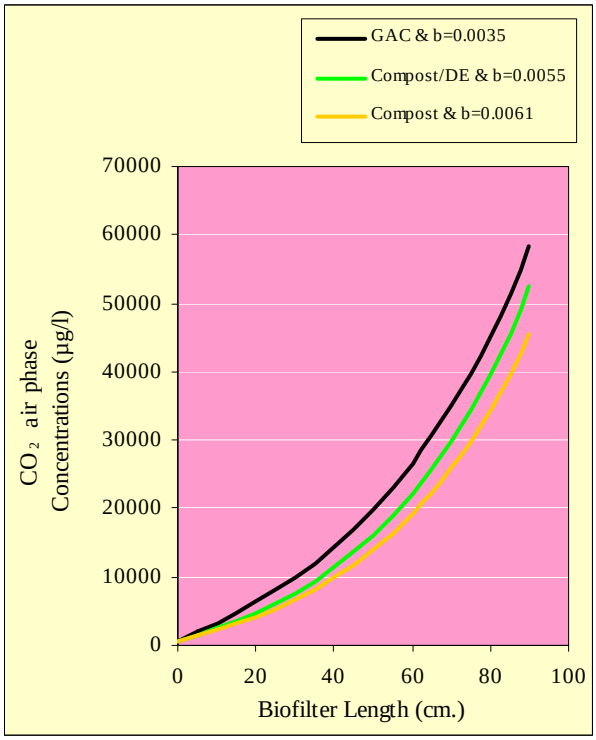

Figure 14: CO_2 concentration profile as a function biofilter length for three different packing materials
(L=90 cm., b ≠ 0)

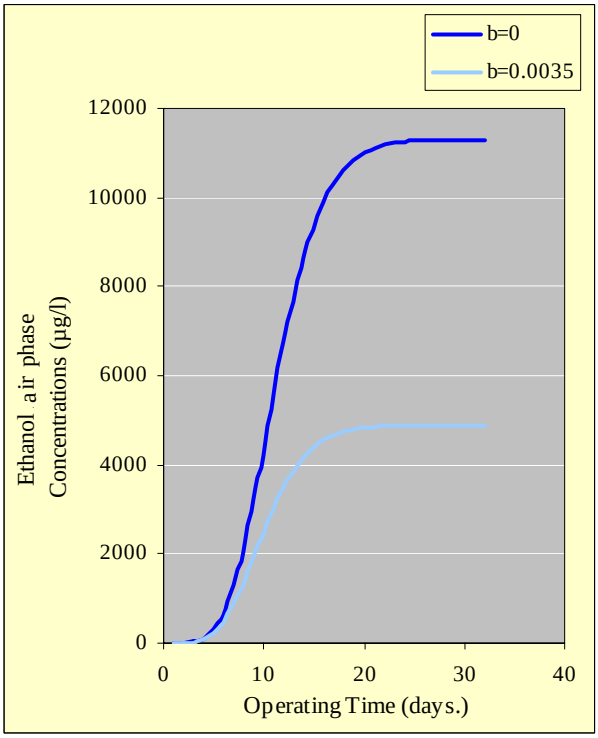

Figure 15: Ethanol concentration profile as a function of operation time for biologically active and inactive system
(L=90 cm., GAC packed biofilter)

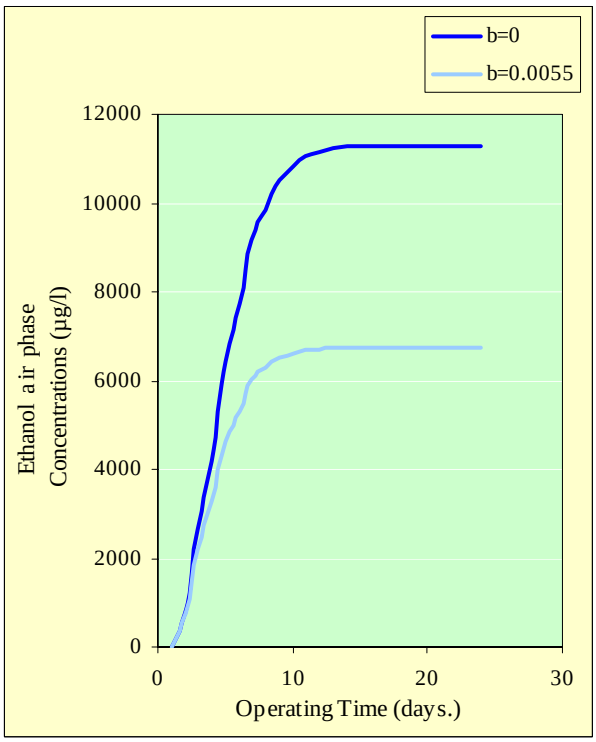

Figure 16: Ethanol concentration profile as a function of operation time for biologically active and inactive system
(L=90 cm., compost/diatomaceous-earth packed biofilter)

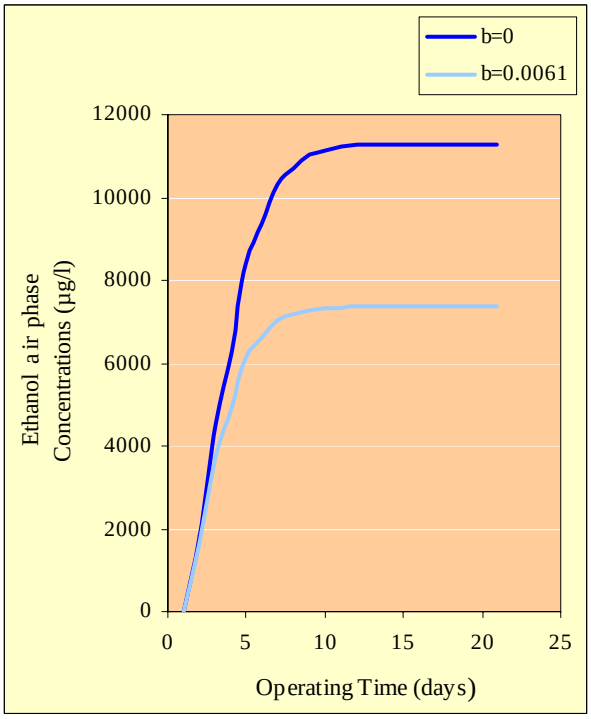

Figure 17: Ethanol concentration profile as a function of operation time for biologically active and inactive system (L=90 cm., compost packed biofilter)

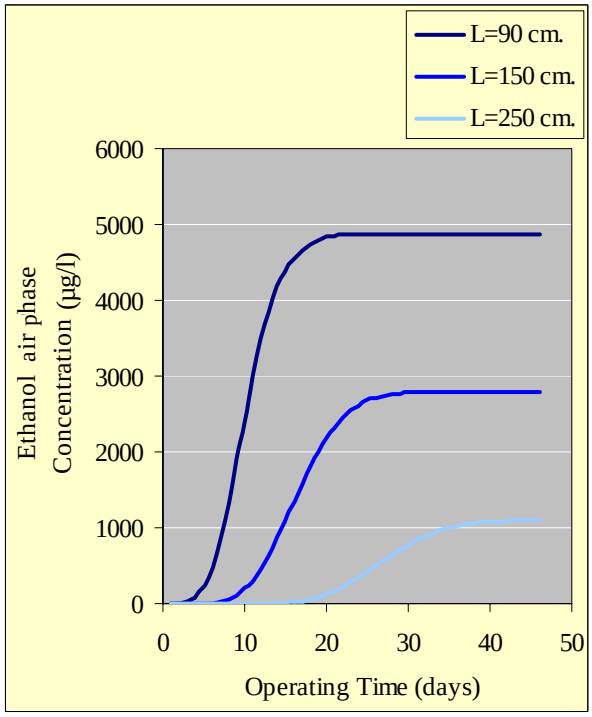

Figure 18: Ethanol concentration profile as a function of operation time and biofilter length (GAC packed biofilter, b=0.0035 h^{-1})

efficiency is decreased up to reaching to a constant capacity of contaminant removal efficiency which is the steady state condition. The time interval to reach to the steady state condition is 20 days for GAC filled biofilter.

5. CO_2 production is increased by time as a result of microbial oxidation of ethanol and the reaction is continued up to reaching to the steady state level.

6. Ethanol removal by GAC filled biofilter is more than that by compost/DE while compost filled one has the less removal efficiency (Figure 13).

7. The order of CO_2 production for different biofilter packing materials is the same as ethanol removal efficiency (item 6 of conclusion) (Figure 14).

This is due to the greater value of k_m, ratio of mass of contaminant in solid/water phase to mass in the air phase, and specific area for GAC. k_m value depends on the values of both k_h, equilibrium value for ratio of constituent concentration in solid/water phase to air phase concentration, and porosity, θ. The porosity of GAC is less than both of compost/DE and compost (0.25 versus 0.45) and its k_h value (k_h=8900) is more than both of compost/DE (k_h=4900) and compost (k_h=3700). As shown in Eq. (10), k_m is directly proportional to retardation factor, R. The average of R for GAC (R=26700) is greater than that of compost/DE (R=5950) and compost (R=4000), i.e., the retention time of contaminants in GAC packed biofilter is greater two other packing. This allows the system to operate in a longer period of time to remove the contaminant. GAC packed biofilter has a greater specific surface area value, also.

8. Biofilter performance is directly affected by biological removal efficiency for a biofilter ($b \neq 0$) is much more than of a conventional filter (b=0).

9. The effluent concentration of ethanol for GAC packed biofilter is less than that of both of compost/DE and compost packed biofilter, i.e., GAC is a better packing and has greater contaminant removal efficiency.

10. For $b \neq 0$, a larger period of time is needed to steady state condition in comparison to the case where b=0 which means a greater contaminant removal efficiency for $b \neq 0$.

11. Increasing the length of biofilter is directly affects on the length of period of time needed to reach to the steady state condition.

12. GAC, compost/DE and compost packed biofilters need 20, 16 and 8 days, respectively, to reach to steady state. After that there is no change in concentration gradient of each species, and the contaminant removal efficiency remains constant.

Notation

C= concentration in air phase (mg/cm^3 air);
D= dispersion coefficient in air phase (cm^2 /hr);
x= distance of travel in filter (cm);
t= time (hr);
V= axial interstitial velocity of air (cm/hr);
C_{ads}= concentration in solid/water phase (mg/ (cm^3 solids/water phase));
θ= filter material porosity at field capacity (dimensionless);
k= transfer rate constant (h^{-1});
k_h= equilibrium value for ratio of concentration in the solids/water phase to air-phase concentration (dimensionless);
b= first-order biodegradation rate constant (h^{-1});
R_c = ratio of mass of carbon dioxide released to mass of substrate degraded (dimensionless);
$[CO_2]_{ads}$= carbon dioxide concentration in solids/water phase (mg/(cm^3 solids/water phase));
$[CO_2]$= carbon dioxide concentration in the air phase (mg/(cm^3 air));
k_c= carbon dioxide transfer rate constant (h^{-1});
k_{hc}= equilibrium value for the ratio of carbon dioxide concentration in the solids/water phase to concentration in the air phase (dimensionless);
M_{ads} = mass of contaminant in the solid/water phase (mg);
M_{air} = mass of contaminant in the air phase (mg); and
CDR= weight of CO_2 evolved per weight of degraded ethanol.
R= retardation factor

References

Abumaizar, R. J., E. H. Smith and W. Kocher, Analytical model of dual-media biofilter for removal of organic air pollutants. J. Environ. Eng., ***123****: 606-614, 1997*

Adler, S. F., Biofiltration – a primer, CEP, 33-41, April 2001, presented at: www.aiche.org/cep/

Alonso, C., M. T. Suidan, B. R. Kim and B. I. Kim, Dynamic mathematic model for the biodegradation of VOCs in a biofilter: biomass accumulation study. Environ. Sci. Technol., ***32****: 3118-3123, 1998*

Alonso, C., M. T. Suidan, G. A. Sorial, F. L. Smith, P. Biswas, P. J. Smith and R. C. Brenner, Gas treatment in trickle-bed biofilters: biomass, how much is enough. Biotechnol. Bioeng., ***54****: 583-594, 1997*

Amanullah, Md., S. Farooq and S. Viswanathan, Modeling and simulation of a biofilter, Ind. Eng. Chem. Res., 38: 2765-2774, 1999.

Baltzis, B. C., S. M. Wojdyla and M. Z. Zarook, Modeling biofiltration of VOC mixtures under steady-state conditions. J. Environ. Eng. (ASCE), ***123****: 599-605, 1997*

Busca, G., and C., Pistarino, Technologies for the abatement of sulphide compounds from gaseous streams: a comparative overview, J. Loss. Prevent. Proc., ***16:*** *363-371, 2003*
available at: www.elsevier.com/locate/jlp

Chitwood, D. E., J. S. Devinny and F.E., Reynolds, Evaluation of a two-stage biofilter for treatment of POTW waste air. Environ. Prog., ***18****: 212-221, 1999*

Chung, Y. C., C. Huang and C. P. Tseng, Biotreatment of ammonia from air by an immobilized Arthrobacter oxydans CH8 biofilter. Biotechnol. Prog., ***13****: 794-798, 1997*

Chung, Y. C., C. Huang and C. P. Tseng, Removal of hydrogen sulfide by immobilized Thiobacillus sp. strain CH11 in a biofilter. J. Chem. Technol. Biot., ***69****: 58-62, 1997*

Cook, L. L., P. A. Gostomski and W. A. Apel, Biofiltration of asphalt emissions: Full-scale operation treating off-gases from polymer-modified asphalt production. Environ. Prog., ***18****: 178-187, 1999*

Dehghanzadeh, R., A., Torkian, B., Bina, H., Poormoghaddas, and A., Kalantary, Biodegradation of styrene laden waste gas stream using a compost-based biofilter, Chemosphere, Article in Press, 2005
available at: www.elsevier.com/locate/chemosphere

de Nevers, N., Air pollution control engineering. McGraw Hill, 2th. Ed., 2000

Deshusses, M. A. and C. T. Johnson, Development and validation of a simple protocol to rapidly determine the performance of biofilters for VOC treatment. Environ. Sci. Technol., ***34****: 461-467, 2000*

Deshusses, M. A., Biological waste air treatment in biofilters. Environ. Biotech., ***8****: 335-339, 1997*

Deshusses, M. A., G. Hamer and I. J. Dunn, Behavior of biofilters for waste air biotreatment. 1. Dynamic model development, Environ. Sci. Technol., ***29****: 1048-1058, 1995a*

Deshusses, M. A., G. Hamer and I. J. Dunn, Behavior of biofilters for waste air biotreatment. 2. Experimental evaluation of a dynamic model. Environ. Sci. Technol., ***29****: 1059-1068, 1995b*

Deshusses, M. A., G. Hamer and I. J. Dunn, Transient-state behavior of a biofilter removing mixtures of vapors of MEK and MIBK from air. Biotechnol. Bioeng., ***49****: 587-598, 1996*

Devinny, J. S., M. A. Deshusses and T. S. Webster, Biofiltration for air pollution control. CRC-Lewis Publishers: Boca Raton, FL., USA, 1999

Dresnack, R. and W. E. Dobbins, Numerical analysis of BOD and DO profiles. J. Sanitary Eng. Div., Proceeding of the ASCE, ***94****: 789-807, 1968*

Elmrini, H., N. Bredin, Z. Shareefdeen, and M. Heitz, Biofiltration of xylene emissions: bioreactor response to variations in the pollutant inlet concentration and gas flow rate, Chem. Eng. J., ***100:*** *149-158, 2004*
available at: www.elsevier.com/locate/cej

Ergas, S. J., K. Kinney, M. E. Fuller and K. M. Scow, Characterization of a compost biofiltration system degrading dichloromethane. Biotechnol. Bioeng., ***44****: 1048-1054, 1994*

Heslinga, D. C. and J. W. Van Groenestijn, In biological waste gas cleaning. Proceedings of an International Symposium, Prins, W. L., J. van Ham, J., (eds.), VDI Verlag: Duesseldorf, Germany, 353-358, 1997

Hodge, D. S. and J. S. Devinny, Biofilter treatment of ethanol vapors. Environ. Prog., ***13****: 167-173, 1994*

Hodge, D. S. and J. S. Devinny, Determination of transfer rate constants and partition coefficients for air phase biofilters. J. Environ. Eng., ***123****: 577-585, 1997*

Hodge, D. S. and J. S. Devinny, Modeling removal of air contaminants by biofiltration. J. Environ. Eng., ***121****: 21-32, 1995*

Hong, J. H., and K. J. Park, Compost biofiltration of ammonia gas from bin composting, Bioresource. Technol., ***96:*** *741-745, 2005*
available at: www.sciencedirect.com

Hwang, S. J., H. M. Tang and W. C. Wang, Modeling of

acetone biofiltration process. Environ. Prog., ***16****: 187-192, 1997*

Jennings, P. A., V. L. Snoeyink and E. S. K. Chian, Theoretical model for a submerged biological filter. Biotechnol. Bioeng., ***18****: 1249-1273, 1976*

Kennes, C., and M.C., Veiga, Fungal biocatalysts in the biofiltration of VOC-polluted air, J. Biotechnol., ***113:*** *305-319, 2004*
available at: www.elsevier.com/locate/jbiotec

Leson, G. and A. M. Winer, Biofiltration: An innovative air pollution control technology for VOC emissions. J. Air Waste Manage. Assoc., ***41****: 1045-1054, 1991*

Martin, G., M. Lemasle and S. Taha, The control of gaseous nitrogen pollutant removal in a fixed peat bed reactor. J. Biotechnol., ***46****: 15-21, 1996*

Miller, M. J., D. G. Allen, Transport of hydrophobic pollutants through biofilms in biofilters, Chem. Eng. Sci., ***59:*** *3515-3525, 2004*
available at: www.elsevier.com/locate/ces

Mohseni, M. and D. G. Allen, Biofiltration of mixture of hydrophilic and hydrophobic volatile organic compounds Chem. Eng. Sci., ***55****: 1545-1558, 2000*

Morgenroth, E., E. D. Schroeder, D. P. Y. Chang and K. M., Scow, Modeling of a compost biofilter incorporating microbial growth. In: R. D. Vidic and F. G. Pohland (eds.), Innovative technologies for site remediation and hazardous waste management. American Society of Civil Engineers, New York, 473-480, 1995

Neal, A. B., and R. C., Loehr, Use of biofilters and suspended-growth reactors to treat VOCs. Waste. Manage., ***20****: 59-68, 2000*

Okkerse, W. J. H., S. P. P. Ottengraf, B. Osinga-Kuipersand and M., Okkerse, Biomass accumulation and clogging in biotrickling filters for waste gas treatment. Evaluation of a dynamic model using dichloromethane as a model pollutant. Biotechnol. Bioeng., ***63****: 418-430, 1999*

Ottengraf, S. P. P. and A. H. C. Van den Oever, Kinetics of organic compound removal from waste gases with a biological filter. Biotechnol. Bioeng., ***25****: 3089-3102, 1983*

Ottengraf, S. P. P., Exhaust gas purification, In: H. J. Rehm and G. Reed (eds), Biotechnology, Weinheim: VCH Verlagsgesel-Ischaft, ***8****: 426-452, 1986*

Schwarz, B. C. E., J. S. Devinny and T. T. Tsotsis, A biofilter network model – importance of the pore structure and other large-scale heterogeneities. Chem. Eng. Sci., ***56****: 475-483, 2001*

Shareefdeen, Z. and B. C. Baltzis, Biofiltration of toluene vapor under steady state and transient conditions: Theory and experimental results. Chem. Eng. Sci., ***49****: 4347-4360, 1994*

Shareefdeen, Z., B. C. Baltzis, Y. S. Oh and R. Bartha, Biofiltration of methanol vapor. Biotechnol. Bioeng., ***41****: 512-524, 1993*

Shojaosadati, S. A. and S. Elyasi, Removal of hydrogen sulfide by the compost biofilter with sludge of leather industry. Resour. Conserv. Recy., ***27****: 139-144, 1999*

Spigno, G., C. Pagella, M. D. Fumi, R. Molteni, and D. M. De Faveri, VOCs removal from waste gases: gas-phase bioreactor for the abatement of hexane by Aspergillus niger, Chem. Eng. Sci., ***58:*** *739-746, 2003. available at: www.elsevier.com/locate/ces*

Swanson, W. J. and R. C. Loehr, Biofiltration: fundamentals, design and operations principles, and applications. J. Environ. Eng., ***123****: 538-546, 1997*

Tang, H. M., S. J. Hwang and S. C. Hwang, Waste gas treatment in biofilters. J. Air Waste Manage. Assoc., ***46****: 349-354, 1996*

Tiwaree, R. S., K. S. Cho, M. Hirai and M. Shoda, Biological deodorization of dimethyl sulfide using different fabrics as the carriers of microorganisms. Appl. Biochem. Biotechnol., ***32****: 135-148, 1992*

Yang, Y. and E. R. Allen, Biofiltration control of hydrogen sulfide, 2. Kinetics, biofilter performance and maintenance. J. Air Waste Manage. Assoc., ***44****: 1315-1321, 1994*

Zarook, S. M., A. A. Shaikh and S. M. Azam, Axial dispersion in biofilters. Biochem. Eng. J., ***1****: 77-84, 1998*

Zarook, S. M., A. A., Shaikh, and Z., Ansar, Development experimental validation and dynamic analysis of a general transient biofilter model. Chem. Eng. Sci., 52: 759-773, 1997

Zarook, S. M. A. A. Shaikh, Z. Ansar and B. C. Baltizis, Biofiltration of volatile organic compound (VOC) mixtures under transient conditions. Chem. Eng. Sci., ***52****: 4135-4142, 1997*

Zarook, S. M. and A. A. Shaikh, Analysis and comparison of biofilter models. Chem. Eng. J., ***65****: 55-61, 1997*