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Biofilter Modeling for Waste Air Treatment: Comparisons of Inherent Characteristics of Biofilter Models

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Abstract−The types of biofilter modeling may be primarily classified in accordance with whether a biofilm is differentiated from other phases in each model. It may be a secondary classification with regard to biofilter-modeling whether sorption volume and/or adsorption are adopted as reservoirs or not. Thirdly, biofilter models are classified as to whether adsorption is assumed to exist through gas phase and/or a biofilm. Among all the biofilter-models of previous investigators all model-components including gas phase, a biofilm, sorption volume and adsorption surface are considered only in the model of Lim. Since his model does not require a numerical solution but an algebraic solution to describe the concentration of organic pollutants in waste-air-streams along the height of a biofilter even under unsteady-state conditions, it satisfies the condition of simplicity that is one of the important model requirements. In spite of its simplicity, Lim's model predictions are fairly good to fit Hodge and Devinny's experimental data.

Key words: Biofilter, Modeling, Adsorption, Biofilm, Sorption Volume

INTRODUCTION

The adoption of biological processes has increasingly been so popular in controlling undesirable compounds in various kinds of wastes that the process of biofiltration has become a promising air pollution technology. Using ambient microbial oxidation to treat large volumes of air with low concentrations of biodegradable VOCs makes the biofiltration technology a more cost-effective process, compared to other VOC control technologies such as carbon adsorption and incineration [Ottengraf, 1986; Ottengraf et al., 1986; Sorial et al., 1995]. Biofilters are known to be superb in two main domains: in the removal of odoriferous compounds [Hirai et al., 1990; Shareefdeen et al., 1993; Park et al., 1993; Tang et al., 1995; Hartikainen et al., 1996; Martin et al., 1996] and in the elimination of volatile organic compounds [Ottengraf, 1986; Ottengraf et al., 1986; Buchner, 1989; Leson and Winer, 1991; Shareefdeen et al., 1993; Deshusses et al., 1993, 1994, 1995, 1996, 1997; Hodge and Devinny, 1994, 1995; Tang et al., 1995; Zarook and Baltzis, 1994; Zarook et al., 1997], primarily solvents, from waste air streams.

In bioreactors pollutant-degrading microbial cultures are naturally immobilized on a packed bed of porous particulates through which a humid air-stream containing pollutants is passed. The technology consists of exposing the contaminated air to a moist film of microbes attached to a stationary synthetic or natural support medium. The volatile organic compounds (VOCs) in the contaminated air sorb into or onto the surfaces of the bed medium long enough for the biodegrading microbes to oxidize the VOCs, converting them into environmentally benign end products such as H_2O and CO_2. Under optimum conditions, the pollutants are fully biodegraded without the formation of aqueous effluents.

It has been reported that highly adsorptive granular activated carbon (GAC) improves the biofilter performance when it is used as a medium. For instance, highly adsorptive capacity of GAC improves steadily trustable operation of biofilter against sudden shock-loading. Moreover, the biofilter using activated carbon as a medium provides such operational advantages over conventional activated carbon adsorbents as that bio-regeneration keeps the maximum adsorption capacity available constantly and the mass transfer zone consequently remains stationary and relatively short. No regeneration of the carbon is required and the bed length is greatly reduced. These features translate into a reduced capital and operating cost. Due to these advantages the biofilter is anticipated to replace some existing applications currently using activated carbon [Liu et al., 1994]. As the demand for biofilters is growing, basic design such as biofilter design and its scale-up becomes necessary, and industrial operations of biofilters need to be understood conceptually, which leads one to investigate and develop biofilter modeling. Consequently, their appropriate models are required to be developed and validated for improved process designs and performances.

Some of the previous works [Ottengraf, 1986; Ottengraf et al., 1986; Hirai et al., 1990; Shareefdeen et al., 1993; Lim, 2000, 2001a: Rittman and McCarty, 1980a, b], compared with each other in this paper, involving biofilter modeling describe the steady states or can be applied to a narrow range of operating conditions. Others [Deshusses and Hamer, 1993; Deshusses and Dunn, 1994; Deshusses et al., 1995; Speitel and Mclay, 1993; Hodge and Devinny, 1994, 1995; Zarook and Baltzis, 1994; Zarook et al., 1997; Amanullah et al., 1999; Lim, 2001b] describe the transient performance of a biofilter with more complicated model parameters than those for steady states.

In this paper various steady state-models and unsteady state-models of a biofilter that have been worked on by previous investigators are classified, as in Tables 1 and 6 respectively, in accordance with their mechanistically involved model-components and phenomenological processes. Subsequently, biofilter-models are discussed on their inherent characteristics including mathematical interpretation and applicability that result from each differentiated classifica-

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tion of methods in biofilter modeling. Then inherent characteristics among various models are compared and evaluated in order to propose which model shall be the appropriate one that satisfies the model-requirements of easy and trustable applicability with relatively small number of model parameters.

Table 1. The components of biofilter model involved to describe its steady state-behavior

	Ottengraf et al. [1986]	Hirai et al. [1990]	Shareefdeen et al. [1993]	Lim [2001a]
Gas phase	○	○	○	○
Biofilm	○	×	○	○
Sorption volume	×	×	×	○
Adsorption with excess capacity	×	×	×	○

Note: ○ and × denote an adopted component and an ignored component, respectively, in each investigators biofilter model.

Table 2. Used model-parameters and experimental parameters of Hodge and Devinny [1995] for a biofilter with the medium of granular activated carbon (GAC)

H	90 cm
D_e	10^{-9} m^2/s
m	0.0035
a	4,500 m^2/m^3
u	23.7 m/hr
C_{go}	11,300 mg/m^3

Table 3. Best-fit parameters by regression analysis by use of model parameters as in Table 2

K	0.103×10^{-6} m^3/mg ($\pm0.003\times10^{-6}$ m^3/mg)
φ	0.01 (lower bound)
l	0.425×10^{-4} m($\pm0.012\times10^{-4}$ m)
Λ	28.6/m($\pm$5.2/m)

Table 4. Sensitivity analysis for the parameters in Table 3 in the form of ten times the fractional change in the error function F minimized that accompanies a ten percent shift in the said parameter, i.e. (δF/F)/(δk/k); δk/k=.1.

K	3.64
φ	N/A
l	1.46
Λ	0.25

METHODS OF MODELING

1. Steady State Modeling

Most investigators [Ottengraf, 1986; Ottengraf et al., 1986; Hirai et al., 1990; Shareefdeen et al., 1993] have worked on the steady-state or quasi-steady-state modeling of a biofilter neglecting the adsorption process into a medium where its medium is saturated with pollutants and lost its ability to adsorb pollutants from the stream of waste air. In addition Lim [2000, 2001a] further derived the general steady state solutions in his comprehensive model-equations of a biofilter for the case of excess adsorption capacity of the medium.

1-1. Model of One Component

1-1-1. Hirai et al.

Hirai et al. [1990] considered a biofilter as a plug flow reactor where biodegradation of Michaelis-Menten type was adopted as a reaction term and compared the experimental data with the steady-state fitting and prediction of their model. The equation of plug flow reactor model is given by Hirai et al. [1990].

$$-\frac{\partial C}{\partial h}=\frac{1}{u}\frac{V_m C}{K_s+C}\beta \tag{1}$$

In their experiments the target component to eliminate in waste air was odorous sulfur compound (e.g., hydrogen sulfide, dimethyl sulfide, methanetiol) and the media was chosen to be peat.

Since they treated a biofilter to be a homogeneous plug reactor there was not any distinction among gas phase (waste air), liquid phase (biofilm), solid phase (media) and any mass transport processes among phases were not considered in their model.

1-2. Model of Two Components

1-2-1. Ottengraf

Table 5. Used model-parameters of Hodge and Devinny for a biofilter with the medium of GAC and compost

	GAC	Compost
H	90 cm	90 cm
D	1,900 cm^2/h	1,200 cm^2/h
ε	0.25	0.45
u	23.7 m/hr	23.7 m/hr
C_{go}	11,300 mg/m^3	1,300 mg/m^3
k^*	0.06/hr	0.06/hr
k_h	9,100	4,500
b_1	0.0035/h	0.0061/h

Table 6. The components of biofilter model involved to describe its transient behavior

	Deshusses et al. [1995]	Zarook et al. [1997]	Hodge and Devinny [1994, 1995]	Amanullah et al. [1999]	Lim [2001b]
Gas phase	○	○	○	○	○
Biofilm	○	○	×	○	○
Sorption volume	○	×	×	×	○
Adsorption (through gas phase)	×	○	○	○	×
Adsorption (through biofilm)	×	×	×	○	○

Note: ○ and × denote an adopted component and an ignored component respectively in each investigator's biofilter model.

Ottengraf [1986] and Ottengraf et al. [1986] made the following assumptions in developing a theoretical model describing the elimination of carbon sources in the biofilter bed.

(1) The mass transfer resistance in the gas-phase is negligible, compared to that in the liquid phase.

(2) The biofilm thickness (l) is much smaller than the diameter of packing particles (i.e., medium) so that the biofilm may be treated as a planar surface.

(3) Substrate transport through the biofilm is made by diffusion.

(4) No limitation occurs except for the substrate.

(5) The interface between gas phase and liquid phase is in the equilibrium.

(6) The Michaelis-Menten kinetics or relationship of Monod is assumed for substrate utilization in the biofilter.

(7) The net growth of biomass in the biofilm is controlled to be "zero" so that one may apply constant kinetic constants.

(8) The biomass is uniformly distributed in the biofilter.

(9) The biofilter is treated as a plug flow reactor.

Two mass balances in biofilm and gas phase are described in their model (Eqs. (2) and (3)) and are given by Ottengraf [1986] and Ottengraf et al. [1986].

$$D_e\frac{d^2C_l}{dx^2}-r_A=0 \quad \text{(Biofilm)} \tag{2}$$

$$-u\frac{dC_g}{dh}=Na \quad \text{(Gas phase)} \tag{3}$$

They adopted the reaction term of first or zero order as a limiting case of Michaelis-Menten type kinetics in a mass balance of biofilm. In case of the first reaction the concentration profile of a target component decays exponentially so that it penetrates through a biofilm. However, when it comes to zero order reaction, the profile of $C_l/(C_g/m)$ behaves in a quadratic manner. Whether a biolayer is fully active or not, the situations are divided into two schemes, i.e., reaction limitation as well as diffusion limitation. It was calculated that critical value of ϕ is $\sqrt{2}$ according to Ottengraf [1986] and Ottengraf et al. [1986], and when the value of ϕ is greater than $\sqrt{2}$ the process is limited by diffusion. Otherwise it is limited by reaction. The criterion of division of the situations is whether C_g is larger than the value of $l^2km/(2D_e)$. When it is larger, it penetrates a biolayer so that the control scheme is a reaction limitation in which the concentration profile of gas phase decreases linearly along the height of a biofilter. In the meantime, when it is less, the scheme is chosen to be a diffusion limitation that leads its profile to quadratic decrease along the height of a biofilter.

1-2-2. Shareefdeen et al.

Shareefdeen et al. [1993] suggested a mathematical modeling of the biofiltration processes of a steady state for the removal of methanol vapor in the stream of waste air, where they used the medium of two volumes of peat with three volumes of perlite particles. Most model parameters were determined in non-biofilter system and assumed the concentration of methanol or oxygen in a biofilm is quite low so that one of both concentrations may be controlling. The differential mass balances in biofilm (Eqs. (4)-(6)) and gas phase (Eqs. (7) and (8)) are given by Shareefdeen et al. [1993].

$$D_M\frac{d^2s_M}{dx^2}=\frac{X_V}{Y_M}\mu(s_M, s_o) \tag{4}$$

$$D_o\frac{d^2s_o}{dx^2}=\frac{X_V}{Y_o}\mu(s_M, s_o) \tag{5}$$

where

$$\mu(s_M, s_o)=\frac{\mu^* s_M}{K'+s_M+(s_M^2/K_I)}\frac{s_O}{K_O+s_O} \tag{6}$$

$$u\frac{dc_M}{dh}=aD_M\left[\frac{ds_M}{dx}\right]_{x=0} \tag{7}$$

$$u\frac{dc_O}{dh}=aD_O\left[\frac{ds_O}{dx}\right]_{x=0} \tag{8}$$

Even though their model was basically the same as that of Ottengraf [1986] and Ottengraf et al. [1986], differential mass balances in biofilm (Eqs. (4) and (5)) and gas phase (Eqs. (7) and (8)) were performed for both components, respectively, where each sink term was expressed as a microbial growth rate divided by each yield coefficient and its specific growth rate (Eq. (6)) was chosen in combination with Haldane type dependence on the methanol concentration and a Monod type dependence of oxygen concentration.

1-3. Model of Four Components

1-3-1. Lim

For all the works of the researchers stated above the effect of the adsorption of organic particles on the medium (i.e., adsorbent) through a biofilm has been ignored even though it has been reported that highly adsorptive granular activated carbon improves the biofilter performance [Liu et al., 1994; Hodge and Devinny, 1994, 1995; Tang et al., 1995; Sorial et al., 1995].

In Lim's works [1999, 2001a, b] the effect of adsorption property of the medium on the biofilter capacity of eliminating organic components in waste gas streams was theoretically discussed and was included in the biofilter model. As the result, the general steady-state solutions in the situations of reaction limiting as well as diffusion limiting were derived for the case of excess adsorption capacity and were compared with the steady-state solutions of Ottengraf [1986] and Ottengraf et al. [1986] where the medium is saturated with pollutants and lost its ability to adsorb them [Lim, 1999, 2001a].

In formulating the model for a biofilter the following assumptions are added to those by Ottengraf [1986] and Ottengraf et al. [1986]:

(1) No catalytic reaction except for adsorption and desorption on the surface of the medium (i.e., beneath the biofilm) exists upon the adsorption of the organic particles.

(2) The dissolved organic compounds are assumed to adsorb on the surface of the medium irreversibly, and the number of vacant adsorption sites of the medium is assumed to be in excess so that the rate of adsorption may not be limited by the number of vacant adsorption sites.

With the above assumptions, the differential equations for the concentration profile of a dissolved organic component (C_l) to be biologically metabolized in the biolayer can be described as:

$$\frac{\partial C_l}{\partial t} = D_e \frac{\partial^2 C_l}{\partial x^2} + r_A \tag{9}$$

The proposed boundary condition at the interface between gas phase (C_g) and liquid phase (wet biolayer) for the governing equation is:

$$C_l(t, x = 0) = \frac{C_g(t, h)}{m} \tag{10}$$

One may assume that the dissolved organic concentration in the sorption volume of the medium (C_s) is uniformly distributed and is continuous at $x=l$, which leads to another boundary condition of $C_l(t,\ x=l)=C_s(t)$. The mass balance in the sorption volume of the medium is described as below:

$$\frac{V_{sorption}}{V}\frac{dC_s}{dt} = -D_e \frac{\partial C_l(t, x = l)}{\partial x} a - k_a(1-\varepsilon)C_s \tag{11}$$

Where k_a is the adsorption constant, that is proportional to the adsorption area per unit volume of adsorbent and a, V, $V_{sorption}$ and ε are the interfacial area of an adsorbent between gas and liquid phases per unit working volume of a biofilter, biofilter bed volume, sorption volume and biofilter bed porosity, respectively.

Since surface diffusion occurs upon adsorption on the surface of a medium and surface diffusion quite prevails over pore diffusion in the actual adsorption phenomena [Hand et al., 1983; Speitel et al., 1987; Speitel and Digiano, 1987], the process of the surface diffusion is lumped in the term of adsorption in R. H. S. of Eq. (11) for the actual adsorption phenomena.

At a steady state, the boundary condition at the interface between the wet biolayer and the medium is formulated as:

$$\frac{\partial C_l}{\partial x}(t, x = l) = -\alpha C_l(t, x = l) \text{ where } \alpha = \frac{k_a(1-\varepsilon)}{D_e a} \tag{12}$$

The governing equations of mass balance in the gas phase and the biofilm are formulated in the same manner as Ottengraf [1986] and Ottengraf et al. [1986] except for a boundary condition (Eq. (12)) at the interface between the biofilm and adsorbents.

1-4. Others

1-4-1. Speitel and Mclay and Others

Speitel and Mclay [1993] and other researchers [Oh and Bartha, 1994; Sorial et al., 1995] described a biofilm trickling biofilter that has another phase of free liquid unlike biofilter and proposed its model that may not be applied to the gas phase biofilter operations without a free liquid phase.

2. Unsteady State Modeling

Previous investigators [Deshusses and Hamer, 1993; Deshusses and Dunn, 1994; Deshusses et al., 1995; Speitel and Mclay, 1993; Hodge and Devinny, 1994, 1995; Zarook and Baltzis, 1994; Zarook et al., 1997; Amanullah et al., 1999; Lim, 2001b] describe the transient performance of a biofilter with more complicated model parameters than those for steady states. Some of them have made an effort on biofilter modeling of process start-up even though the phenomenological behavior of its process start-up is not easy to describe since it is too complicated during the developing period of biolayer. Others focused on the transient model applicable to transitions from one set of operating conditions to another.

2-1. Model of Two Components

2-1-1. Hodge and Devinny

Hodge and Devinny [1994, 1995] assumed the biofilm and the medium to be a single phase in which the first-order biodegradation of sorbed pollutants by microsomes is performed and solved numerically the differential equations of mass balance in both gas phase (Eq. (13)) and liquid/solid phase (Eq. (14)) for the profile of the pollutant concentrations along the biofilter. The differential mass balance equations (Eqs. (13) and (14)) and other approximated equations (Eqs. (15)-(19)) are given by Hodge and Devinny [1995].

$$\frac{\partial C_g}{\partial t} + V'\frac{\partial C_g}{\partial x} = D\frac{\partial^2 C_g}{\partial x^2} - \left(\frac{1-\varepsilon}{\varepsilon}\right)[k^*(k_h C - q')] \tag{13}$$

$$\frac{\partial q'}{\partial t} = k^*(k_h C - q') - b_1 q' \tag{14}$$

Neglecting dispersion term in Eq. (13), it reduces into:

$$\frac{\partial C_g}{\partial t} + V'\frac{\partial C_g}{\partial x} = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{\partial q'}{\partial t} + b_1 q'\right) \tag{15}$$

When q' is assumed to be in equilibrium with C_g, i.e., $q'=k_h C_g$, Eq. (15) becomes:

$$\frac{\partial C_g}{\partial t} + V'\frac{\partial C_g}{\partial x} = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(k_h\frac{\partial C_g}{\partial t} + b_1 k_h C_g\right) \tag{16}$$

Thus Eq. (16) reduces in compact form as Eq. (17).

$$\frac{\partial C_g}{\partial t} + V'\frac{\partial C_g}{\partial x} = -k_m\frac{\partial C_g}{\partial t} - b_1 k_m C_g \tag{17}$$

where $k_m = k_h\left(\frac{1-\varepsilon}{\varepsilon}\right)$

Eq. (17) can be rearranged as below.

$$\frac{\partial C_g}{\partial t} + \frac{V'}{R}\frac{\partial C_g}{\partial x} = -\frac{b_1 k_m}{R} C_g \tag{18}$$

where $R = 1 + k_m = 1 + k_h\left(\frac{1-\varepsilon}{\varepsilon}\right)$

R is called retardation factor and it may be calculated when a peak velocity (V/R) is experimentally measured with concentration peak analysis.

At steady state, Eq. (18) becomes:

$$\varepsilon\frac{\partial C_g}{\partial x} = (1-\varepsilon)\frac{b_1 q'}{V'} \tag{19}$$

2-2. Model of Three Components

2-2-1. Deshusses et al.

Deshusses et al. [1995] adopted not only the assumptions for biofilter modeling made by Ottengraf [1986] and Ottengraf et al. [1986] but also the definition of sorption volume that is the pore volume filled with water inside the medium of a biofilter to describe the transient behaviour of the biofilter performance. They proposed a biofilter model, which is composed of a gas phase, a biofilm and a sorption volume, as in Fig. 1, to account for sorption and adsorption phenomena that are a controlling part of unsteady biofiltration processes. They considered that pollutants (MEK and/or MIBK) diffuses from the gas phase before they are degraded in the biofilm and are accumulated in the sorption volume as a reservoir, that is defined as the difference between the volume of water in the system and that of the biofilm. The difference equations for their mass

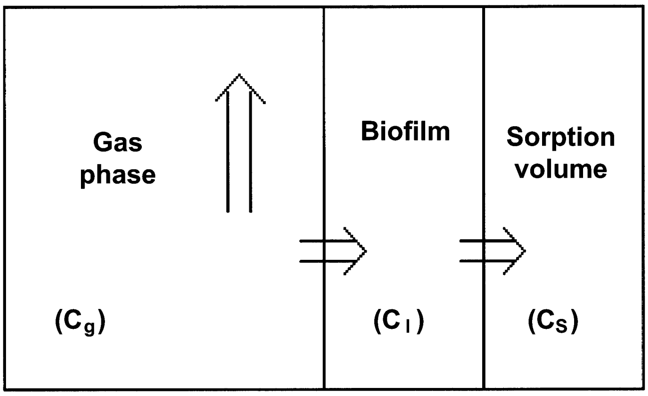

Fig. 1. Schematic diagram of a biofilter-model where a biofilm is treated as a planar surface.

balances were solved numerically for the concentration profile of pollutants along the height of biofilter. The media used were equal volumes of compost and polystyrene as a support material.

The following are three difference equations (Eqs. (20)-(22)) on gas phase, biofilm and sorption volume respectively, given by Deshusses et al. [1995].

$$\frac{V\varepsilon}{W}\frac{dC_{j,W}}{dt}=G(C_{j,W-1}-C_{j,W})-N_{j,W}\frac{aV}{W}$$

where V=AH, G=uA, j=component (Gas phase: W=1, 2, …, 10) (20)

$$\frac{aV}{W}\frac{l}{M}\frac{dS_{j,M,W}}{dt}=D_e\frac{aV}{W}\left(\frac{S_{j,M-1,W}-S_{j,M,W}}{l/M}-\frac{S_{j,M,W}-S_{j,M+1,W}}{l/M}\right)-R_{S_{j,M,W}}\frac{aV}{W}\frac{l}{M}$$

where $S_{j,0,W}=\frac{C_{j,W}}{H_j}$ (Biofilm: M=1, …, 4) (21)

$$\frac{V_{sorption}}{W}\frac{dS_{j,5,W}}{dt}=D_e\frac{aV}{W}\left(\frac{S_{j,4,W}-S_{j,5,W}}{l/M}\right)\text{ (Sorption volume)} \tag{22}$$

2-2-2. Zarook et al.

Zarook and Baltzis [1994] and Zarook et al. [1997] extended their steady-state model [Shareefdeen et al., 1993] to describe the transient performance of the biofilters where the adsorption of the pollutant on the biofilter medium occurs only through the direct bare solid/air interface and adsorption does not occur through biofilm/solid interface that is the fraction of γ from whole interfacial area of the media according to their model. Zarook et al. [1997] have generalized the model of Zarook and Baltzis [1994] to include the dispersion term in the mass balances of gas phase. Like other investigators Zarook and Baltzis [1994] regarded a biofilter to consist of three sections. The differential mass balance equations (Eqs. (23)-(28)) of three sections are given by Zarook and Baltzis [1994].

1) Mass balances in the biofilm:

$$\frac{\partial s_j}{\partial t}=f(X_V)D_{jW}\frac{\partial^2 s_j}{\partial x^2}-\frac{X_V}{Y_j}\mu_j(s_j,s_o) \tag{23}$$

$$\frac{\partial s_O}{\partial t}=f(X_V)D_{OW}\frac{\partial^2 s_O}{\partial x^2}-\frac{X_V}{Y_{Oj}}\mu_j(s_j,s_o) \tag{24}$$

where

$$\mu(s_j,s_O)=\frac{\mu_j^* s_j}{K_j'+s_j+(s_j^2/K_{ij})}\frac{s_O}{K_{Oj}+s_O} \tag{25}$$

2) Mass balances in the gas phase:

$$\varepsilon\frac{\partial c_j}{\partial t}=-u\frac{\partial c_j}{\partial h}+D_{jW}f(X_V)\gamma a\left[\frac{\partial s_j}{\partial x}\right]_{x=0}-k_a'(1-\gamma)a(c_j-c_j^*) \tag{26}$$

$$\varepsilon\frac{\partial c_O}{\partial t}=-u\frac{\partial c_O}{\partial h}+D_{OW}f(X_V)\gamma a\left[\frac{\partial s_j}{\partial x}\right]_{x=0} \tag{27}$$

3) Mass balances in the solid phase particles

$$(1-\varepsilon)\rho_p\frac{\partial q_j}{\partial t}=k_a'(1-\gamma)a(c_j-c_j^*) \tag{28}$$

where $q_j=K(c_j^*)^n$

2-3. Model of Four Components

2-3-1. Amanullah et al.

Amanullah et al. [1999] made the model of Zarook et al. [1997] more generalized and more complicated even though two models are basically same except for a few additional considerations. Those equations (Eqs. (29)-(32)) taken into account for the model of Amanullah et al. are given by Amanullah et al. [1999] and summarized in detail below.

(1) There exists adsorption to adsorbents through a biolayer, which provides a typical boundary condition at the interface between a biofilm and adsorbents.

$$-D_i\gamma a\left[\frac{\partial s_i}{\partial x}\right]_{x=l}=k_{i,l-ads}(q^*_{i,g-ads}-q'_i) \tag{29}$$

(2) The mass balance of adsorbed pollutants in adsorbents includes an adsorption through a biolayer as well as a primary adsorption through gas phase.

$$\frac{\partial q'}{\partial t}=\gamma k_{i,l-ads}(q^*_{i,g-ads}-q'_i)+(1-\gamma)k_{i,g-ads}(q^*_{i,g-ads}-q'_i)-R_{i,ads} \tag{30}$$

(3) The mass balance of adsorbed pollutants in adsorbents includes the sink term of biodegradation in the adsorbent, which is expressed as nth-order reaction.

$$R_{i,ads}=k_{rxn,i}q'^{n}_i \tag{31}$$

(4) Adsorption isotherm is expressed linearly with pollutant concentration in the gas phase using distribution coefficient of a pollutant in an air/solid media system.

$$q^*_{i,g-ads}=c_i/m_{2,i} \tag{32}$$

They suggested that specific surface area for mass transfer and biofilm thickness primarily contribute to an excellent biofilter-performance. In addition, it was further suggested higher adsorptive support media are necessary to be used for stable and easy load fluctuations handling.

2-3-2. Lim

In Lim's work a new approach to include the effect of adsorption property of the medium on the capacity of eliminating organic components for waste air treatments in the biofilter modeling was presented. As in the previous 4th article of Steady State Modeling, the mathematical model and its relevant solutions under various limiting conditions for the waste air treatment with a biofilter were presented for the case of excess adsorption capacity [Lim, 1999, 2001a]. However in most cases vacant adsorption sites become occupied by organic components from waste air stream and the rate of adsorption is limited as the adsorption continuously proceeds. Thus the transient behaviour of the biofilter is controlled by adsorption [Hodge and Devinny, 1994, 1995] or sorption with negligible adsorption [Deshusses et al., 1995]. The former was recently modeled by Lim [2001b] so that the unsteady state-governing equations for mass balance are solved analytically in order to be easily interpreted and to be applied to the industrial unsteady state-operations of a biofilter. Among the additional assumptions made for the previous model for the case of excess adsorption capacity assumption 2 should be replaced by "2) The dissolved organic particles are assumed to adsorb on the surface of the medium reversibly and the rate of adsorption is limited by the number of remaining vacant adsorption sites."

The surface diffusion coefficient of GAC is ca. 10^{-15} m^2/sec [Hand et al., 1983; Speitel et al., 1987a; Speitel and Digiano, 1987b], which is so much less than the effective diffusion coefficient, D_e, in the biolayer (i.e., 10^{-9} m^2/sec) that the surface diffusion process inside the medium is very much slower than the diffusion process through the biolayer. These experimental evidences lead to such a quasi-steady-state assumption that the diffusion flux through the biolayer is generated as soon as the surface diffusion inside the medium occurs. Thus the assumption of quasi-steady-state of Eq. (11) is supported and validated to reduce into Eq. (12) even for unsteady state-conditions (i.e., in time scale of adsorption process).

In modeling the transient behavior of the biofilter, the clouding effect is applied to k_a in order to explain that as the adsorption proceeds, the occupancy of vacant adsorption sites results in the limited adsorption velocity and in order to consider the reversible adsorption process. Thus the adsorption constant, k_a is now expressed as below.

$$k_a = k'a'\left(1-\frac{q}{q_\infty}\right) \tag{33}$$

Consequently, its mass balance in the medium becomes:

$$\frac{dq}{dt} = \frac{k'a'}{w}\left(1-\frac{q}{q_\infty}\right)(1-\varepsilon)VC_s \tag{34}$$

where a', w, q, and q_∞ are the adsorption area per unit volume of a medium, medium mass, adsorbed pollutant mass per unit mass of a medium, and pollutant mass adsorbed in equilibrium with that in the liquid phase per unit mass of a medium, respectively.

Substituting Eq. (33) for k_a into the expression of a from Eq. (12) to apply the clouding effect, one gets:

$$\alpha = \Lambda\left(1-\frac{q}{q_\infty}\right) \text{ where } \Lambda = \frac{k'a'(1-\varepsilon)}{D_e a} \tag{35}$$

and one may assume that α varies in a slower manner like q does, than such a variable as C_l in the biofilm does. Then the quasi-steady state of the mass balance in the biofilm is assumed and its quasi steady-state solution is available where α is expressed as in Eq. (35). From its quasi-steady-state solution one gets a quasi-steady-state flux at the interface between a liquid phase and a medium (i.e., N) and may substitute it into the mass balance of organic pollutants in the gas phase of a biofilter (Eq. (36)).

$$\varepsilon\frac{\partial C_g}{\partial t} + u\frac{\partial C_g}{\partial h} = -Na \tag{36}$$

After the new variable, θ=t−h/V' where V'=u/ε, is introduced, L. H. S. and R. H. S. of Eq. (36) are reduced into:

$$V'\left.\frac{\partial C_g}{\partial h}\right|_\theta = -Na/\varepsilon \tag{37}$$

After Eq. (37) is integrated with h, assuming that α is weak fuction of h for a given entrance time of the waste air stream to a biofilter column and treating α as a constant average value set while the waste air stream that entered into a biofilter column at a given entrance time (θ), travels along the biofilter bed height (H), the solution of Eq. (36) for the case of first order-biodegradation is obtained as:

$$\frac{C_g}{C_{go}} = e^{-N_r N_\phi \zeta}\overline{H}\left(t-\frac{h}{u/\varepsilon}\right) \tag{38}$$

where ϕ, N_r, N_ϕ and $\overline{H}$ denotes $l\sqrt{\frac{k}{D_e}}$, $\frac{HD_e\phi a}{ulm}\tanh\phi$, $\dfrac{\dfrac{\sinh\phi+\frac{\alpha}{\phi/l}\cosh\phi}{\cosh\phi+\frac{\alpha}{\phi/l}\sinh\phi}}{\tanh\phi}$, and Heavyside step function, respectively. Considering that a quasi-steady state of the mass balance in the biofilm is assumed and the time scale of interest of the biofilter operation is much longer than $\frac{h}{u/\varepsilon}$, Eq. (38) may be treated as a simple exponential function without $\overline{H}\left(t-\frac{h}{u/\varepsilon}\right)$ as below.

$$\frac{C_g}{C_{go}} = e^{-N_r N_\phi \zeta} \tag{39}$$

The pollutant mass adsorbed per unit mass of medium in equilibrium with that dissolved per unit volume of the liquid phase (q_∞) is assumed to be KC_l (σ=1) according to a Freundlich model with n=1 for its simplicity and it is substituted in Eq. (35). Then one gets:

$$q = \left(1-\frac{\alpha}{\Lambda}\right)K\frac{\frac{C_g}{m}}{\left(\cosh\phi+\frac{\alpha}{\phi/l}\sinh\phi\right)} \tag{40}$$

Eq. (12), which is the boundary condition at x=l of the mass balance in the biofilm, is substituted into the mass balance of the adsorbed pollutant mass per unit mass of medium (Eq. (41)) as below:

$$\frac{\partial q}{\partial t} = -D_e\left.\frac{\partial C_l}{\partial x}\right|_{x=l} a(V/w) \tag{41}$$

One gets:

$$\frac{\partial q}{\partial t} = \frac{\frac{C_g}{m}D_e a(V/w)\alpha}{\left(\cosh\phi+\frac{\alpha}{\phi/l}\sinh\phi\right)} \tag{42}$$

As the adsorbed pollutant mass per unit mass of medium (q) that is initially zero before the waste gas containing pollutants entered into biofilter bed, becomes saturated, the value of α that is initially Λ, approaches zero. One may derive the expression of $\frac{\partial\alpha}{\partial t}$ from the chain rule of $\frac{\partial q}{\partial t}=\frac{\partial q}{\partial\alpha}\frac{\partial\alpha}{\partial t}$. Thus dividing Eq. (42) by $\frac{\partial q}{\partial\alpha}$ that comes from a partial derivative of q with α after substituting Eq. (39) into Eq. (40), the expression of $\frac{\partial\alpha}{\partial t}$ is derived as below.

$$\frac{\partial\alpha}{\partial t}=\frac{D_e a(V/w)\alpha\left(\cosh\phi+\frac{\alpha}{\phi/l}\sinh\phi\right)^2}{K\left[-\frac{1}{\Lambda}\left(\cosh\phi+\frac{\alpha}{\phi/l}\sinh\phi\right)^2-\left(1-\frac{\alpha}{\Lambda}\right)\frac{\sinh\phi}{\phi/l}\left(\cosh\phi+\frac{\alpha}{\phi/l}\sinh\phi\right)-\left(1-\frac{\alpha}{\Lambda}\right)\frac{D_e a}{m}\frac{h}{u}\right]} \tag{43}$$

Separating the variables on both sides of Eq. (43) and integrating both sides, one can derive the implicit expression of α as follows.

$$t=\frac{K}{D_e a(V/w)}\Bigg[-\Bigg(\frac{1}{\phi/l}\tanh\phi+\frac{1}{\Lambda}+\frac{D_e a}{m}\left(\frac{h}{u}\right)\left(\frac{1}{\cosh\phi}\right)^2\Bigg)\left(\ln\frac{\alpha}{\Lambda}-\ln\frac{\frac{\alpha}{\phi/l}\sinh\phi+\cosh\phi}{\frac{\Lambda}{\phi/l}\sinh\phi+\cosh\phi}\right)+\left(\frac{D_e a}{m}\right)\left(\frac{h}{u}\right)\left(\frac{\tanh\phi}{\phi/l}+\frac{1}{\Lambda}\right)\left(\frac{1}{\frac{\Lambda}{\phi/l}\sinh\phi+\cosh\phi}-\frac{1}{\frac{\alpha}{\phi/l}\sinh\phi+\cosh\phi}\right)\left(\frac{\sinh\phi}{\phi/l}\right)^{-1}\Bigg] \tag{44}$$

Applying the value of the model parameters from various experiments for the performance of biofilter [Ottengraf, 1986; Shareefdeen et al., 1993; Deshusses et al., 1995; Deshusses and Dunn, 1994; Deshusses and Hamer, 1993; Speitel and Mclay, 1993; Liu et al., 1994; Hodge and Devinny, 1994, 1995], the profiles of the concentration of pollutants from waste gas streams along the biofilter height and the value of the experimental time corresponding to a given value of α are obtained analytically from Eqs. (39) and (44), respectively.

3. Numerical Integration

Both partial differential equations of Eqs. (13) and (14) were integrated simultaneously to compare the results of model-prediction of Hodge and Devinny [1995] with those of Lims model for both cases of GAC medium and compost medium of a biofilter. For the case of the medium of GAC the results of model-prediction of Hodge and Devinny were available in their work. [Hodge and Devinny, 1995] However these partial differential equations were integrated in this paper to confirm if their predictions had been correct since it was found that their two experimental times (i.e., the fourth day and the twentieth day) were mismatched to their prediction-times (i.e., the fifth day and the nineteenth day). In the case of the medium of compost they did not perform the model-predictions in their work so that one may judge the model applicability to other medium than GAC medium of a biofilter. For simultaneous numerical integrations of two partial differential equations, Compaq Visual Fortran Standard Edition (Version 6.6) was used as a Fortran compiler and both mathematical and statistical IMSL libraries were linked to a source program in order to utilize the subroutines including DMOLCH for double precision from IMSL Fortran 90 MP Library (Version 4.01).

RESULTS AND DISCUSSION

Many researchers [Bibeau et al., 2000; Jorio et al., 1998; Wu et al., 1998, 1999; Kiared et al., 1997; Leson and Smith, 1997] have performed steady-state-experiments on elimination capacities of a biofilter in response to different volumetric loadings of organic pollutants in gas phase. They found that increasing elimination capacity of most hydrophobic components generally characterizes a diffusional limitation in the relatively small range of volumetric loadings. However most hydrophobic components are found to behave in the manner of a reaction limitation beyond their critical volumetric loadings so that their elimination capacities reach their biological reaction limit. According to Ottengraf [1986] and Ottengraf et al. [1986] they become kal in case of reaction control while kaδ in case of diffusion control. Unlike Ottengraf [1986] and Ottengraf et al. [1986], Hirai et al. [1990] did not differentiate a biofilm and gas phase so that they assumed a biofilter as a single phase-plug flow reactor. Thus their model is considered as the most primitive one with the advantage of model simplicity. However it has to depend on curve fitting procedures to experimental data rather than mechanistic approach due to the absence of any mass transport processes among phases. Shareefdeen et al. [1993] developed Ottengraf's model to include another mass balance of a controlling substrate-concentration in their model. Since specific growth rates of microbial activity may be a controlling step in their experiments, given-controlling information renders the above differential mass balance equations into quasi-steady state equations. Thus these quasi-steady state equations may be treated as unsteady state problems in their controlling time scale. In the meantime general steady-state solutions in various limiting situations are derived analytically for the case of excess adsorption capacity and compared with those of Ottengraf [1986] and Ottengraf et al. [1986] as one of their special operating conditions. [Lim, 1999, 2001a] Thus, as a special case, when the value of α becomes zero the boundary condition of Eq. (12) reduces into that of Ottengraf [1986] and Ottengraf et al. [1986] so that the media lose the adsorption ability. When first-order kinetics is used in the substrate utilization rate, as the value of α increases, the corresponding values of $C_l/(C_g/m)$ and C_g/C_{go} become lower at a given value of ϕ, through the thickness of the biofilm and the height of the biofilter, respectively. However the effect of α becomes insignificant when the value of ϕ becomes larger than a certain number, i.e., ca 2. It may be strongly associated with that the critical value of ϕ for zero-order kinetics is $\sqrt{2}$ according to Ottengraf [1986] and Ottengraf et al. [1986], and that when the value of ϕ is greater than $\sqrt{2}$ the process is limited by diffusion. With zero-order kinetics in the substrate utilization rate, for both situations of reaction limiting and diffusion limiting, their steady-state solutions were obtained. For both cases their analytical solutions were confirmed to reduce into those of Ottengraf [1986] and Ottengraf et al. [1986] when the value of a becomes zero. As in Table 1 the components involved in steady state-biofilter modeling of previous investigators are factorized in accordance with the type of their phases as well as phenomenological processes.

In the unsteady state-model of Deshusses et al. [1995], it was under such a situation that adsorption might be negligible rather than sorption in the sorption volume. Thus the adsorption through a liquid/solid interface mostly inside the medium was not considered. Even though the definition of a sorption volume was adopted in their model in order to consider adsorption as well as sorption phenomena, the component of sorption volume is not able to explain the effect of adsorption in the mechanistic approach as long as the concentration gradient in the sorption volume is employed as a driving force of diffusive mass transfer. In addition their model contains too many model parameters and would be better to be simplified in terms of the hierarchy of the model with the aid of process lumping. Zarook and Baltzis [1994] and Zarook et al. [1997] assumed that the adsorption of the pollutant on the biofilter medium occurs only through the direct bare solid/air interface to use a certain value of mass transfer coefficient between the gas phase and the solid phase of adsorbent and that adsorption does not occur through biofilm/solid interface that is a certain fraction (γ) of whole interfacial area of the media according to their model. In a biofilter, moisture is continuously provided through the pre-humidification of the inlet gas stream because moisture content of the filter bed is a critical factor for the successful operation of a biofilter. The humidity of inlet gas stream is even raised above 99 percent for the optimum performance of biofilters [Wani et al., 1997]. Lith [1997] and Auria et al. [1997] suggested the moisture content in a biofilter medium be between 40% and 60% by wet weight for its optimum-sustained performance. As a result of normal biofilter operation, however, the pore space is filled with a condensed liquid phase and the bare solid surface of a biofilter medium is still covered with liquid layer even though there are patches of biofilm on the solid surfaces on the medium. Thus, it is not realistic that a dried bare solid/air interface without liquid layer exists in the normal performance of a biofilter. Even if it exists, it was reported that the adsorption capacity for toluene was decreased with increasing relative humidity through the bare solid/air interface. The effect of water vapor was greater at the lower toluene concentration. [Gong and Keener, 1993; Chou and Chiou, 1997] Moreover, in their model, the fraction of total surface area for biofilm formation, that is significantly varying during a start-up period as they observed, was introduced and, however, was treated as a constant. Thus they confined their model to be applied to such a biofilter medium as a peat, that has relatively small adsorption capacity so that the adsorption process through a biofilm to the biofilter medium may be neglected, and faced the dilemma between a complicated phenomenological modeling and their simple but incorrect treatment. Besides their partial differential equations from the mass balance of a gas phase, a biofilm and a solid phase need to be numerically integrated for their general solutions and even for their approximate solutions.

In the modeling of Hodge and Devinny [1994, 1995] their control volume approach was different from that of Ottengraf [1986] and Ottengraf et al. [1986] and it stemmed from basic equations for adsorption in an adsorption column except that the sink term by biological degradation in liquid/solid phase was considered in Eq. (14), while there exists no reaction term in the process of adsorption column. However, since they lumped the phenomena of both a liquid phase (biofilm) and a solid phase (medium), the effects of adsorption of a medium as well as biological degradation in a biolayer were not separately illustrated and were not explained.

It is notable that in the model of Amanullah et al. [1999] they added the term of adsorption through a biofilm to the model of Zarook et al. so that their model could explain actual phenomena through the biofilm at highly expensive cost of model-complexity. However, they adopted the difference of $q^*_{i,g-ads}$ and q'_i instead of $q^*_{i,l-ads}$ and q'_i as a driving force of mass transfer between liquid phase and solid phase (Eq. (30)) so that the mass-balance equation of solid phase (Eq. (30)) could be uncoupled with that of liquid phase. Thus the model of Amanullah et al. [1999] basically belongs to the model of Zarook et al. [1994, 1997] in that it was a difference between the concentration of a pollutant in solid (or gas) phase and its corresponding equilibrium concentration in gas (or solid) phase used as a driving force even for mass transfer between liquid phase and solid phase. In contrast, Lim [2001b] suggested a simplified unsteady state-biofilter model in use of process lumping, which may be applied to the biofilter system in which adsorption by media should be considered for its normal operation. It is meaningful that Lim [1999, 2001a, b] was the first one who considered that biofilter consists of gas phase, biofilm (fixed liquid phase), sorption volume and adsorption surface in the media, even though his general models were developed based on those of Ottengraf [1986] and Ottengraf et al. [1986] and the definition of sorption volume in his model was devised by Deshusses et al. [1995]. The surface diffusion coefficient of GAC was measured as ca 10^{-15} m^2/sec [Hand et al., 1983; Speitel et al., 1987a; Speitel and Digiano, 1987b] and is so much less than the effective diffusion coefficient, D_e, in the biolayer by the order of six. In Lim's model a quasi-steady state assumption in sorption volume of the media (adsorbents) is supported and validated by these experimental evidences. Fig. 2 shows the model-predictions of Lim [2001b] with best-fit parameters as in Table 3 and Table 4 obtained by regression analysis (Fig. 3) using model param-

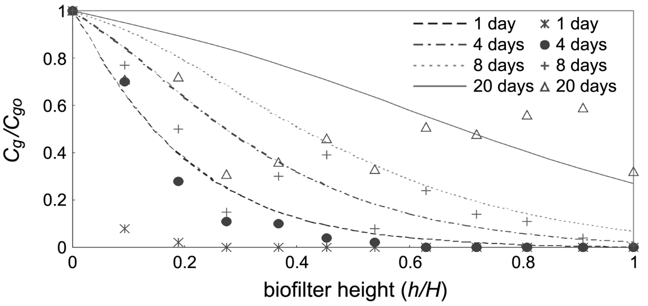

Fig. 2. Model predictions of the distribution of C_g/C_{go} of unsteady experimental data [Hodge and Devinny, 1995] along the height of a GAC biofilter at given experimental times.

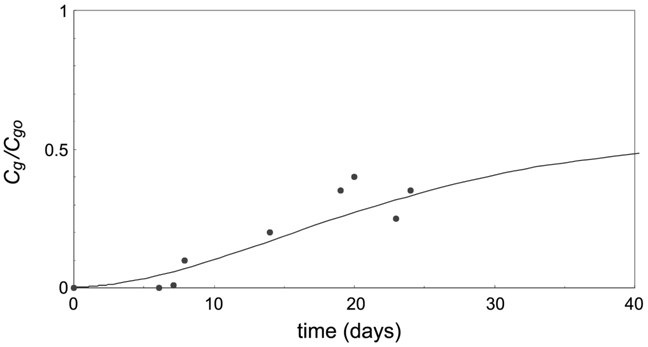

Fig. 3. Best-fit from unsteady experimental data [Hodge and Devinny, 1995] of C_g/C_{go} at the exit of a GAC biofilter.

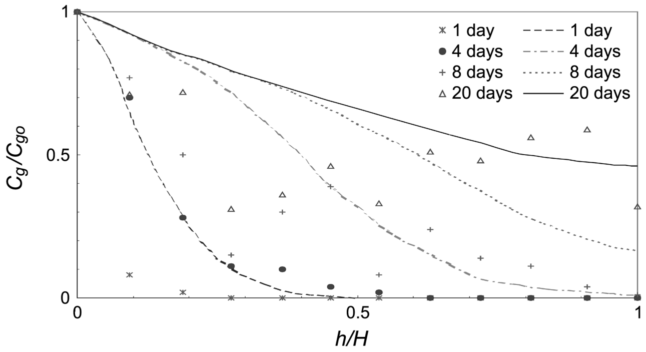

Fig. 4. Model-fitting of C_g/C_{go} of unsteady experimental data [Hodge and Devinny, 1995].

eters as in Table 2. The values of error between experimental data [Hodge and Devinny, 1995] and predictions by Lim's model (Fig. 2) and by the model of Hodge and Devinny (Fig. 4) were estimated by the method of absolute least square. The values of summation of square errors were turned out to be 2.157 and 3.315 in case of Lim's model and the model of Hodge and Devinny respectively. Therefore, the prediction of Lim's model was more accurate by 53.7% than that of the model of Hodge and Devinny. Lim's model contains fewer model parameters (Table 2 and 3) than the other models except for the model of Hodge and Devinny. The numbers of necessary parameters and algebraic equations from Lim's model are ten (Table 2 and Table 3) and three (Eqs. (39), (40) and (44)), respectively, while the model of Hodge and Devinny contains eight parameters as in Table 5 (less by two) and two differential equations (Eqs. (13) and (14)), respectively, since Hodge and Devinny [1995] extended the famous model equations for conventional adsorption column to a biofilter and lumped the phenomena of both a liquid phase (biofilm) and a solid phase (medium) as in Table 6, in their model where the effects of the adsorption of a medium as well as biological degradation in biofilm were not separately illustrated and were not explained. For unsteady state-biofilter modeling the components that previous investigators adopted or involved to establish their biofilter models are shown in Table 6.

The simplicity of Lim's model comes from the fact that:

(1) It contains all model components as in Tables 1 and 6 with relatively fewer model parameters so that each model component (e.g., gas phase, biofilm, sorption volume and adsorption) may be separately explained. However, the model of Hodge and Devinny [1995] contains only two model components mechanistically involved.

(2) The number of necessary equations to solve is three (Eqs. (39), (40) and (44)). However, it is extremely simple and easy to solve those equations because:

a) These are algebraic equations unlike the other models.

b) Since α is used as an intermediate variable in Eq. (44) uncoupled with the other equations (i.e., Eqs. (39) and (40)), one may substitute the value of α from Eq. (44) into Eqs. (39) and (40) to obtain the concentration of pollutant mass in gas phase and in adsorbents (i.e., medium), respectively.

Figs. 5 and 6 show another Lim's model-predicted breakthrough-curve at the exit of a biofilter with the medium of compost and his model-predicted distribution of VOC concentration along the height of a biofilter with the medium of compost, respectively, with the aid of used model parameters as shown in Table 7. Figs. 7 and 8 are model predictions by Hodge and Devinny with the model parameters as in Table 5 (compost) corresponding to Figs. 5 and 6, respectively. It may be observed without any help of statistical means that Lim's model predictions (Figs. 5 and 6) are more comparable

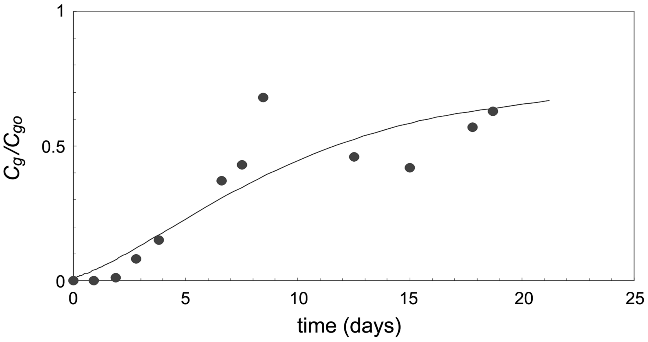

Fig. 5. Lim's model-predicted time evolutions of C_g/C_{go} of unsteady experimental data [Hodge and Devinny, 1995] at the exit of a biofilter (i.e., h/H=1) with the medium of compost.

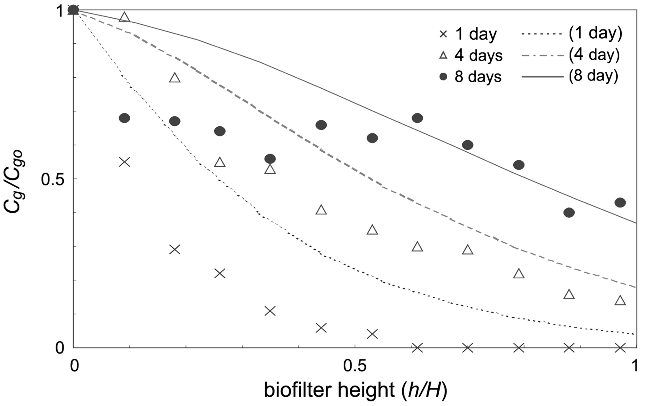

Fig. 6. Model predictions of the distribution of C_g/C_{go} of unsteady experimental data [Hodge and Devinny, 1995] along the height of a biofilter with the medium of compost at given experimental times.

Table 7. Used Lim's model-parameters for a biofilter with the medium of GAC and compost

	GAC	Compost
H	90 cm	90 cm
D_e	10^{-9} m^2/s	10^{-9} m^2/s
m	0.0035	0.0035
a	4,500 m^2/m^3	3,300 m^2/m^3
u	23.7 m/hr	23.7 m/hr
C_{go}	11,300 mg/m^3	11,300 mg/m^3
K	0.103×10^{-6} m^3/mg	0.515×10^{-7} m^3/mg
φ	0.01	0.0093
l	0.425×10^{-4} m	0.425×10^{-4} m
Λ	28.6/m	38.6/m

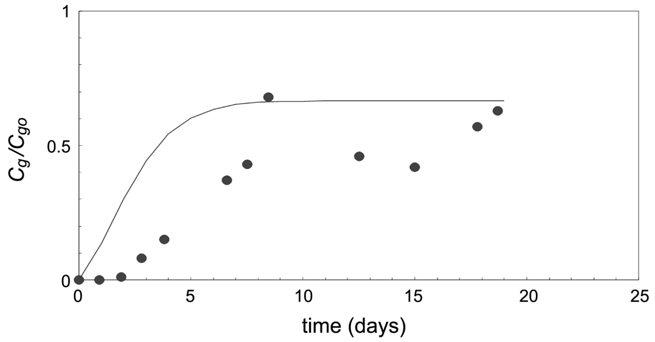

Fig. 7. Hodge and Devinny's model-predicted time evolutions of C_g/C_{go} of unsteady experimental data [Hodge and Devinny, 1995] at the exit of a biofilter (i.e., h/H=1) with the medium of compost.

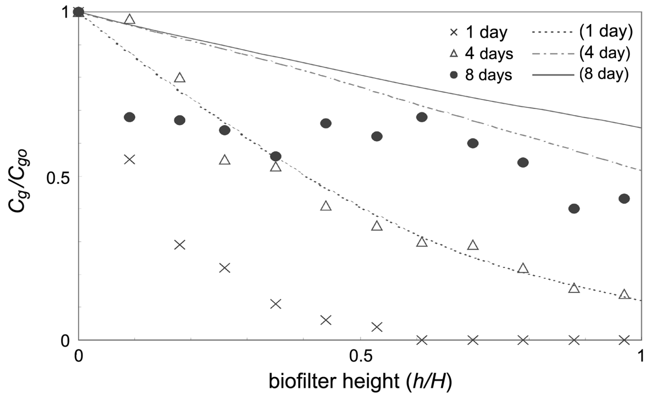

Fig. 8. Model predictions of the distribution of C_g/C_{go} of unsteady experimental data [Hodge and Devinny, 1995] along the height of a biofilter with the medium of compost at given experimental times.

to the experimental data [Hodge and Devinny, 1995] than their predictions (Figs. 7 and 8). The parameter values of Lim's model for the case of the compost-medium were assumed to be the same as those for the GAC medium except for interfacial area (a), Thiele modulus (ϕ) and Freundlich adsorption isotherm constant (K), based upon their experimental results with the medium of compost as well as GAC. These two parameters of Thiele modulus (ϕ) and Freundlich adsorption isotherm constant (K) for the medium of compost were chosen by the following reasoning (The interfacial areas (a) for both media were calculated as shown in Table 7 with given values of diameters (0.1 cm) (not shown in Tables) and porosities (ε) of both media from Table 5).

(1) The value of Thiele modulus (ϕ) for the compost-medium may be estimated as that for the GAC-medium multiplied by $\sqrt{\frac{k_{compost}}{k_{GAC}}}$ assumming the thickness of biofilm (l) is same for both media. With regard to the eliminating capacity (EC) of a biofilter it may be expressed for 1st order reaction scheme as: EC=$kalC_l^{AV}$ in Lim's model where C_l^{AV} denotes such an averaged pollutant concentration in a biolayer as $\frac{\int_0^l C_l(x)xdx}{l}$ while EC=b_1q'V(1−ε) in the model of Hodge and Devinny where q' may be assumed to be in equilibrium with C_g (i.e., q'=k_hC_g). Equating both expressions of EC and substituting the parameter values from Tables 5 and 7, one can calculate the value of $\frac{k_{compost}}{k_{GAC}}$ assuming the value of $\frac{C_g}{C_l^{AV}}$ for the medium of GAC may be applicable to the biofilter operation with the medium of compost.

(2) For the case of the compost medium, the value of K was assumed to be proportional to the equilibrium value for the ratio of the concentrations in the solids/water phase to that in the air phase (k_h).

The analysis by the comparison between the cases of GAC-medium and compost-medium led us to identify the values of ϕ and K for the case of the compost-medium as 0.93 times and half as large as the values of those for the case of the GAC-medium respectively as in Table 7.

CONCLUSIONS

Some of biofilter-modeling compared in this paper describes the steady states or can be applied to a narrow range of operating conditions. Others describe the transient performance of a biofilter with more complicated model parameters than those for steady states. According to the number of model components mechanistically involved in their modeling, steady state models and unsteady state models dealt with in this paper are classified as in Tables 1 and 6, respectively.

The types of biofilter modeling may be primarily classified in accordance with whether a biofilm is differentiated from other phases in each model. The phase of a biofilm was excluded in the biofilter models of Hirai et al. [1990] and Hodge and Devinny [1994, 1995]. In the former the whole components of a biofilter including a biofilm are assumed to be homogeneous, and in the latter a biofilm and solid phase are assumed to be a single phase. It may be secondary classification with regard to biofilter modeling whether sorption volume and/or adsorption are adopted as reservoirs or not. Deshusses et al. [1995] adopted the definition of sorption volume to describe transient behavior of biofilter in relatively shorter time scale than that of the adsorption process. Other investigators on unsteady state-biofilter modeling [Hodge and Devinny, 1994, 1995; Zarook and Baltzis, 1994; Zarook et al., 1997; Amanullah et al., 1999; Lim, 2001b] applied the process of adsorption in their models. It is notable that both sorption volume and adsorption are considered in the model of Lim [2001b]. Thirdly, biofilter models are classified as to whether adsorption is assumed to exist through gas phase and/or through a biofilm. Investigators [Hodge and Devinny, 1994, 1995; Zarook and Baltzis, 1994; Zarook et al., 1997] adopted the adsorption only through gas phase in the modeling of biofilter. Later Amanullah et al. [1999] considered the adsorption through both gas phase and a biofilm in their model that is inherently the same as that of Zarook et al. [1997]. In particular, all model-components including gas phase, a biofilm, sorption volume and adsorption surface are considered only in the model of Lim [2001b]. Besides, a proper treatment on the mass balance of a sorption volume provided necessary information to analytically solve the concentration profile in a biofilm. He adopted the clouding effect in k_a in order to explain reversible adsorption processes when the adsorption capacity is limited as the vacant adsorption sites on the surface of a medium are occupied. This model may be applied to unsteady-state operations of a biofilter with the possible minimum number of model parameters and with the required time scale that industry calls for. Since his model does not require a numerical solution but an algebraic solution to describe the concentration of organic pollutants in waste-air-streams along the height of a biofilter even under unsteady-state conditions, it satisfies the condition of simplicity that is one of the important model requirements. In spite of its simplicity Lim's model predictions were fairly good to fit Hodge and Devinny's experimental data.

ACKNOWLEDGMENT

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NOMENCLATURE

A : area of cross section of biofilter

a : interfacial area per unit of volume [m^2/m^3]

a' : adsorption area per unit volume of medium [m^2/m^3]

b_1 : first-order biological rate constant [sec^{-1}]

C : concentration of odor compound [ppm]

C_j^* : concentration in the gas phase in equilibrium [kg/m^3]

C_g (or C_j): concentration in the gas phase [kg/m^3]

C_{g0} : inlet concentration in the gas phase [kg/m^3]

C_l (or S_j): concentration in the liquid phase of biofilm [kg/m^3]

C_M : concentration of methanol in the air [kg/m^3]

C_O : concentration of oxygen in the air [kg/m^3]

C_s : concentration in the liquid phase of sorption volume [kg/m^3]

D : constituent dispersion coefficient in the gas phase [m^2/sec]

D_e : effective diffusivity in the biofilm [m^2/sec]

D_i : diffusion coefficient of pollutant i in the biofilm [m^2/sec]

D_{jw} : diffusion coefficient of pollutant j in water [m^2/h]

D_M : diffusion coefficient of methanol in the biofilm [m^2/h]

D_o : diffusion coefficient of oxygen in the biofilm [m^2/h]

D_{ow} : diffusion coefficient of oxygen in water [m^2/h]

$f(X_V)$: ratio of diffusivity of a compound in the biofilm to that in water

H : biofilter bed height [m]

H_j : Henry coefficient of component j

$\overline{H}$: Heaviside step function

h : height coordinate of biofilter bed [m]

K : Freundlich isothermal constant [$\left(\frac{m^3}{kg}\right)^n\left(\frac{mg}{solid-g}\right)$]

$K'_{(j)}$: constant in the specific growth expression of a culture growing on compound j [kg/m^3]

$K_{I(j)}$: inhibition constant in the specific growth expression of a culture growing on compound j [kg/m^3]

$K_{O(j)}$: constant in the specific growth expression of a culture, expressing the effect of oxygen [kg/m^3]

K_m : Michaelis-Menten constant [kg/m^3]

K_s : saturation constant [ppm]

k : reaction rate constant of first-order [sec^{-1}] or zero-order [kg/m^3sec]

k' : intrinsic adsorption constant [m/sec]

k^* : transfer rate constant [sec^{-1}]

k_a : adsorption constant [sec^{-1}]

k'_a : mass transfer coefficient between the gas and the solid particle [m/h]

k_h : equilibrium value for the ratio of constituent concentration in solids/water phase to air phase concentration

$k_{i,\,g-ads}$: mass-transfer coefficient of component i between the gas phase and the solid particle [sec^{-1}]

$k_{i,\,l-ads}$: mass-transfer coefficient of component i between the liquid phase and the solid particle [sec^{-1}]

k_m : ratio of mass of contaminant in solids/water phase to mass in air phase

l : biofilm thickness [m]

M : number of division (biofilm)

m : distribution coefficient

$m_{2,\,i}$: distribution coefficient for the substance i in an air/solid media system

$N_{(j)}$: diffusive flux at the interface between gas phase and liquid phase [$kg/m^2\cdot sec$]

N_r : decay constant in the absence of adsorption of medium

N_ϕ : ratio of decay constants between the cases when adsorption exists and is absent

$q_{(j)}$: adsorbed substrate mass per unit solid mass [mg/solid-g]

q' : constituent concentration in solids/water phase [mg/cm^3]

q_∞ : adsorbed substrate mass per unit solid mass in equilibrium with that dissolved in the biofilm (σ=1) [mg/solid-g]

q'_i : concentration of pollutant i on the solid particle [g/cm^3]

$q^*_{i,\,g-ads}$: adsorbed concentration of pollutant i on the solid particle in equilibrium with that in the gas phase [g/cm^3]

$q^*_{i,\,l-ads}$: adsorbed concentration of pollutant i on the solid particle in equilibrium with that in the liquid phase [g/cm^3]

R : retardation factor

$R_{i,\,ads}$: rate of degradation of component i in the adsorbed phase [$g/cm^3/sec$]

R_{s_j} : rate of degradation of component j in the biofilm [$kg/m^3/sec$]

r_A : reaction rate [$kg/m^3\cdot sec$]

S_M : methanol concentration in the biofilm [kg/m^3]

S_o : oxygen concentration in the biofilm [kg/m^3]

t : time [sec]

u : approach velocity of waste gas stream [m/sec]

V : bed volume [m^3]

V_m : maximum biological degradation rate [g-S/sec/kg-dry peat]

V' : interstitial velocity [m/sec]

$V_{sorption}$: sorption volume [m^3]

W : number of division (gas phase)

w : mass of medium [g]

X_V : biofilm density [kg dry cells/m^3]

x : depth coordinate of biofilm [m]

Y_M : yield coefficient on methanol [kg biomass/kg methanol]

Y_O : yield coefficient on oxygen [kg biomass/kg oxygen]

Greek Letters

α : ratio of $ka(1-\varepsilon)$ to D_ea [m^{-1}]

β : conversion coefficient [kg-dry peat/g-S]

γ : fraction of total surface area available for biofilm formation

δ : effective biolayer thickness

ε : bed porosity

θ : time for a waste air stream to enter into a biofilter [sec]

Λ : value of α of a clean medium

$\mu_{(j)}$: specific growth rate [h^{-1}]

$\mu^*_{(j)}$: constant in the specific growth rate expression [h^{-1}]

ρ_p : density of solid particle [g/m^3]

ζ : dimensionless height of a biofilter, h/H

σ : dimensionless depth coordinate of biofilm

ϕ : Thiele number for first-order reaction

ϕ_0 : Thiele number for zero-order reaction

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