The time dependent characteristics of waste gas treatment with biofilter

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It has been reported that highly adsorptive granular activated carbon improves the biofilter performance. In this work the theoretical effect of adsorption property of the medium, to the biofilter capacity of eliminating organic components in waste gas stream, is thoroughly discussed. The characteristics of this model does not require a numerical solution but a simple analytic algebraic solution to express the concentration of organic pollutant in waste air stream even under unsteady operating condition. Thus the modified model would satisfy the important model requirement of simplicity and would be an unique model that is able to explain the theoretical effect of adsorption capacity of medium to the pollutant removal efficiency of biofilter.

Introduction

Using ambient microbial oxidation to treat large volumes of air with low concentrations of biodegradable VOCs makes biofiltration technology a more cost-effective process, compared to other VOC control technologies such as carbon adsorption and incineration. Moreover the biofilter using activated carbon as a medium provides several operational advantages over conventional activated carbon adsorbents. Hence the biofilters is anticipated to replace some existing applications currently using activated carbon.

Materials and method

Many investigators have worked on the steady or quasi steady state modeling of biofilter neglecting adsorption process into medium where its medium is saturated with pollutants and lost its ability to adsorb pollutants from the stream of waste air.[1),2),3)] Deshusses *et al.*[4)], Hodge and Devinny[5),6)], Zarook and Baltzis[7)], Zarook *et al.*[8)] proposed a biofilter model which is able to account for unsteady biofiltration processes. In this work, the theoretical effect of adsorption property of the medium, to the biofilter capacity of eliminating organic components in waste gas stream, is intensively discussed and is included in biofilter model. Besides governing equations for mass balance are solved analytically rather than numerically in order to be easily interpreted and to be applied to the industrial operation of biofilter. In formulating a model for biofilter the same assumptions are made as Ottengraf [2)] did.

The case of excess adsorption capacity:

With the above assumptions, the differential equations for the concentration profile of dissolved organic component (C_l) to be biologically metabolized in the biolayer, may be described with the boundary condition in equilibrium at the interface between gas phase (C_g) and liquid phase (wet biolayer) and another boundary condition at the other end of biolayer. One may assume that the dissolved organic concentration in sorption volume of the medium(C_s) is uniformly distributed and is continuous at $x=l$, which leads to another boundary condition of $C_l(t, x = l) = C_s(t)$. Then the mass balance in the sortion volume is generated and one might possibly assume such a quasi-steady state that diffusion flux through biolayer is generated as soon as surface diffusion inside medium occurs. Thus, at steady-state, the boundary condition at the interface between the wet biolayer and adsorbent (packing material), is possibly formulated with the definition of $\alpha = \dfrac{k_a(1-\varepsilon)}{D_e a}$, using the above assumption.

1. The solution for steady state

1.1. First order kinetics

For the Michaelis-Menten or Monod constant, $K_m >> C_l$, it becomes that it approaches 1st order kinetics in substrate utilization rate (*i.e.*, $\dfrac{\mu_m}{Y}\dfrac{C_l}{C_l + K_m}X$ where Y is the cell yield coefficient and X is the active

microorganism concentration). With the 1st order kinetics, the solution becomes

$$\frac{C_l}{C_g/m} = \frac{\cosh\{\phi(1-\sigma)\} + \frac{\alpha}{\phi/l}\sinh\{\phi(1-\sigma)\}}{\cosh\phi + \frac{\alpha}{\phi/l}\sinh\phi} \quad (1)$$

where Φ (*i.e.*, $\sqrt{\frac{k}{D_e}}$) is the Thiele number and σ (*i.e.*, $\frac{x}{l}$) is the dimensionless coordinate in the biolayer thickness.

One should notice that with α =0, the solution of C_l reduces to the solution of Ottengraf[2], *i.e.*, $C_l/(C_g/m) = \frac{\cosh\{\phi(1-\sigma)\}}{\cosh\phi}$. In this manner, one may obtain the steady-state solution of the treated waste air as below:

$$\frac{C_g}{C_{g_0}} = e^{-N_r N_\phi \zeta} \quad (2)$$

where ζ, C_{g0}, N_r and N_ϕ are the dimensionless height of the biofilter, the concentration of untreated inlet waste gas, $\frac{HD_e\phi\alpha}{ulm}\tanh\phi$ and $\frac{\sinh\phi + \frac{\alpha}{\phi/l}\cosh\phi}{\cosh\phi + \frac{\alpha}{\phi/l}\sinh\phi}\tanh\phi$ respectively. It is noteworthy that with α =0 N_ϕ becomes unity and independent of the value of Φ and the solution of eq. (9) reduces to the solution of Ottengraf[2] (i.e, $\frac{C_g}{C_{g_0}} = e^{-\frac{HD_e\phi\alpha}{ulm}\zeta\tanh\phi}$).

1.2. Zero order kinetics

1.2.1. reaction limitation

In this case, their is no diffusion limitation which makes the biolayer fully active upto the whole biolayer thickness, *l*. Then the solution is:

$$\frac{\frac{C_l}{C_g}}{m} = \frac{1}{2}\frac{\phi_0^{\,2}}{C_g/C_{g_0}}\left(\sigma^2 - \left(\frac{2+\alpha l + 2\frac{C_g/C_{g_0}}{\phi_0^{\,2}}\alpha l}{1+\alpha l}\right)\sigma\right) + 1 \quad (3)$$

where $\phi_o = l\sqrt{\frac{km}{D_e C_{go}}}$

With α =0, eq.(11) becomes: $\frac{C_l}{\frac{C_g}{m}} = \frac{1}{2}\frac{\phi_o^{\,2}}{\frac{C_g}{C_{go}}}(\sigma^2 - 2\sigma) + 1$, which is identical to the solution of Ottengraf.[2] For the treated outlet concentration of waste air, one may get:

$$\frac{C_g}{C_{g_0}} = \frac{-\frac{klm}{D_e\alpha}(1+\frac{\alpha}{2}l)}{C_{g_0}} + \left(1+\frac{\frac{klm}{D_e\alpha}(1+\frac{\alpha}{2}l)}{C_{g_0}}\right) e^{-\frac{HD_e a}{um}\frac{\alpha}{1+\alpha l}\zeta} \qquad (4)$$

As α approaches zero, eq. (13) becomes: $\frac{C_g}{C_{go}} = 1 - \frac{KH}{uC_{go}}\zeta$, where $K=kal$ (i.e., maximum elimination capacity), which is identical to the expression of C_g/C_{go} by Ottengraf.[2]

1.2.2. diffusion limitation

One may consider the case when diffusion limitation just occurs, *i.e.*, aqueous concentration of dissolved organic material becomes zero at σ =1. Then the solution becomes independent of the value of α and becomes identical to that of Ottengraf.[2]

The case of limiting adsorption capacity:

In kinetically modeling of this section, the clouding effect is applied to α in order to explain that as adsorption proceeds, occupancy of adsorption site results in the limited adsorption velocity and in order to consider the reversible adsorption process. The quasi-steady state of pollutant concentration in biofilm may be possibly assumed and assuming that α is a weak fuction of h for a given entrance time (i.e., $\theta = \theta^*$) of waste air stream to biofilter column and that one may treat α as a constant value or an average value while waste air stream that entered into biofilter column at a given entrance time, travels along the biofilter bed height, H. The solution of pollutant concentration from treated waste air may be obtained. The pollutant mass adsorbed in equilibrium with that in the liquid phase per unit mass of medium, q_∞, is assumed to be in accordance with a Freundlich model with n=1 for its simplicity. Then The pollutant mass adsorbed per unit mass of medium , q, may be expressed in terms of α and C_g. The reqired boundary condition is substituted into the mass balace of adsorbed pollutant mass per unit mass of medium, q , and one may get the expression of accumulation rate of the pollutant mass adsorbed per unit mass of medium. Separating the variables on both sides of the expression of time derivative of α and integrating its both sides, one may derive the implicit expression of α as follows.

$$t = \frac{K}{D_e a(V/w)}\left[-\left(\frac{1}{\phi/l}\tanh\phi + \frac{1}{\Lambda} + \frac{D_e a}{m}\left(\frac{h}{u}\right)\left(\frac{1}{\cosh\phi}\right)^2\right)\left(\ln\frac{\alpha}{\Lambda} - \ln\frac{\frac{\alpha}{\phi/l}\sinh\phi + \cosh\phi}{\frac{\Lambda}{\phi/l}\sinh\phi + \cosh\phi}\right) + \right.$$
$$\left.\left(\frac{D_e a}{m}\right)\left(\frac{h}{u}\right)\left(\frac{\tanh\phi}{\phi/l} + \frac{1}{\Lambda}\right)\left(\frac{1}{\frac{\Lambda}{\phi/l}\sinh\phi + \cosh\phi} - \frac{1}{\frac{\alpha}{\phi/l}\sinh\phi + \cosh\phi}\right)\left(\frac{\sinh\phi}{\phi/l}\right)^{-1}\right] \qquad (5)$$

Result and discussion

The best fit parameters are determined by regression analysis adopting Kirkpatrick's Monte Carlo-simulated annealing with use of given model parameters from various experiments for the performance of biofilter. At the exit of biofilter bed the time evolution of ethanol concentration in treated waste air

stream is predicted with best-fit parameters in comparison with the experimental data of Hodge and Devinny.[6] The prediction is fairly well consistent to the experimental data of them.

Nomenclature

C_g	concentration in the gas phase (kg/m^3)
C_{go}	inlet concentration in the gas phase (kg/m^3)
C_l	concentration in the liquid phase of biofilm (kg/m^3)
C_s	concentration in the liquid phase of sorption volume (kg/m^3)
x	depth coordinate of biofilm (m)
σ	dimensionless depth coordinate of biofilm
l	biofilm thickness (m)
m	distribution coefficient
D_e	effective diffusivity in biofilm (m^2/sec)
r_A	reaction rate (kg/m^3· sec)
a	interfacial area per unit of volume (m^2/m^3)
V	bed volume (m^3)
k	reaction rate constant of first order (sec^{-1}) or zero order (kg/m^3· sec)
ϕ	Thiele number
Λ	The value of α of clean medium(m^{-1})
H	biofilter bed height (m)
h	height coordinate of biofilter bed (m)
u	approach velocity of waste gas stream (m/sec)
ϕ_o	Thiele number for zero order reaction
q	adsorbed substrate mass per unit GAC mass (mg/GACg)

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