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Mathematical modeling of gas phase and biofilm phase biofilter performance

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ABSTRACT

In this paper, mathematical models of biofilteration of mixtures of hydrophilic (methanol) and hydrophobic (α-pinene) volatile organic compounds (VOC's) biofilters were discussed. The model proposed here is based on the mass transfer in air–biofilm interface and chemical oxidation in the air stream phase. An approximate analytical expression of concentration profiles of methanol and α-pinene in air stream and biofilm phase have been derived using the Adomian decomposition method (ADM) for all possible values of parameters. Furthermore, in this work, the numerical simulation of the problem is also reported using the Matlab program to investigate the dynamics of the system. Graphical results are presented and discussed quantitatively to illustrate the solution. Good agreement between the analytical and numerical data is noted.

1. Introduction

Different cleaning technologies of gaseous effluents have been developed. Among these technologies, biological methods are increasingly applied for the treatment of air polluted by a wide variety of pollutants. Biofilteration is certainly the most commonly used biological gas treatment technology. Biofilteration involves naturally occurring microorganisms immobilized in the form of biofilm on a porous medium such as peat, soil, compost, synthetic substances or their combination.

The medium provides to the microorganisms a hospitable environment in terms of oxygen, temperature, moisture, nutrients and pH. As the polluted airstream passes through the filter-bed, pollutants are transferred from the vapor phase to the biofilm developing on the packing particles [1,2].

Recently Li et al. [3] as well as other research groups [4–10] have investigated emissions of VOCs into the atmosphere. Currently, biological control processes have become an established technology for air pollution control. Biological control processes have many advantages over traditional methods such as lower operating fees and less secondary pollution, which

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is rather true for the removal of readily biodegradable VOCs at low concentrations, so these processes are investigated largely and widely. Bioreactors for VOC removal can be classified as biofilters, bio scrubbers, biotrickling filters, or rotating drum biofilters, and choice of reactors should be based on many factors including the characteristics of the target VOCs [11–15].

In order to control the emission of volatile organic compounds (VOC) like methanol, α-pinene, etc. from industries, biofilters are being used nowadays instead of chemical complex absorption method [16–20]. Biofilters offer two major advantages to an energy-starved country like India. A mathematical model is describing the dynamic physical and biological processes occurring in a packed trickle-bed air biofilters to analyze the relationship between biofilter performance and biomass accumulation in the reactor [4].

For the treatment of mixed VOCs [21–23], the presence of methanol and α-pinene in the air stream significantly influenced the removal of pollutants. The removal capacity for methanol and α-pinene per unit volume of the bed decreased linearly with increasing loading rates of methanol and α-pinene. The presence of this easily biodegradable compound suppressed the growth of the methanol and α-pinene degrading microbial community, thereby decreasing methanol and α-pinene removal capacity of the biofilters. Some researchers have studied the biofitration of pure methanol [24–26] and pure α-pinene [27,28].

Recently, few researchers have studied the biofitration of mixtures of pure methanol and pure α-pinene. Also a few researchers have tried to examine the treatment of mixtures of hydrophobic and hydrophilic VOCs and to understand the interactions between these compounds despite the fact that this situation exists in larger amount of air emissions. Mohseni and Allen [16] developed a mathematical model for methanol and α-pinene removal in VOC's biofilteration. Lim et al. [29] developed the steady state solution of biofilter model only for the limiting cases (first order and zero order kinetics). Also Lim et al. [30,31] obtained the non-steady solution of biofilter model using numerical methods. Recently some authors [32,33] solved the non-linear problems using fractional reduced differential transform method (FRDTM). To the best of our knowledge, to date, a rigorous analytical expression of concentrations of substrate in the biofilm phase and air phase has been reported. The purpose of this communication is to derive approximate analytical expressions for the concentrations in both the phases using the Adomian decomposition method [34–40].

2. Mathematical modeling of the boundary value problem

The mathematical model relating the biofiltration of blends of hydrophilic and hydrophobic VOCs is based on the biophysical model proposed by Mohseni and Allen [16]. It includes two main processes of diffusion of the compounds methanol and α-pinene through the biofilm and their degradation in the biofilm. Fig. 1 illustrates a schematic diagram of a single particle, in the biofilter, covered with a uniform layer of biofilm in which the simultaneous biodegradation of methanol and α-pinene takes place. The experimental setup for the biofilteration of this organic compound is given in Fig. 2.

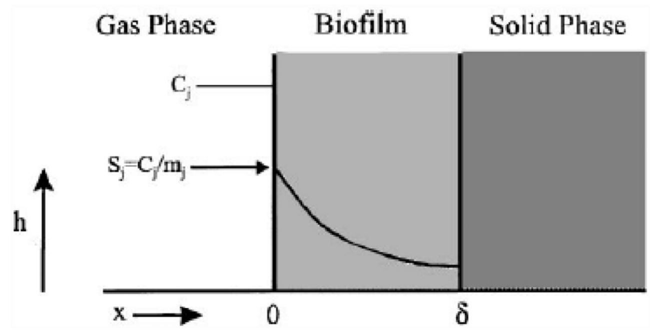

Fig. 1 – Biophysical model for the biofilm structure on the biofilters packing materials and the concentration profiles across the biofilm.

2.1. *Mass balance in the biofilm phase*

The removal of methanol and α-pinene in the biofilm at steady state is described by the following system of non-linear differential equations (Mohseni and Allen [16]):

$$D_{em}\frac{d^2S_m}{dx^2}=\frac{X}{Y_m}\frac{\mu_{\max(m)}S_m}{K_m+S_m} \tag{1}$$

$$D_{ep}\frac{d^2S_p}{dx^2}=\alpha\frac{X}{Y_p}\frac{\mu_{\max(p)}S_p}{K_p+S_p} \tag{2}$$

where S_m and $S_p$represent the concentration of methanol and α-pinene respectively. $\mu_{\max}$, K, Y, D_e and x are maximum specific growth rate, half saturation constant, yield coefficient, effective diffusion coefficient and the distance respectively. Subscripts m and p represent methanol and α-pinene respectively. The dry cell density in the biofilm X represents the overall population of microorganisms that consist of methanol and α-pinene degraders. The coefficient for the effect of methanol on α-pinene biodegradation is defined as follows:

$$\alpha=1/(1+(C_m/K_i))^2 \tag{3}$$

where K_i and C_m are the inhibition constant and the concentration of methanol in the air phase respectively. The boundary conditions are

$$S_m=\frac{C_m}{m_m}=S_{im}\text{ and }S_P=\frac{C_P}{m_P}=S_{ip}\text{ at }x=0 \tag{4}$$

$$\frac{dS_m}{dx}=\frac{dS_P}{dx}=0\text{ at }x=\delta \tag{5}$$

2.2. *Mass balance in gas phase*

The concentrations of methanol and α-pinene in the air, along the biofilter column, are described by

$$U_g\frac{dC_m}{dh}=A_sD_{em}\left[\frac{dS_m}{dx}\right]_{x=0} \tag{6}$$