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Analysis of a dual liquid phase biofilter for the removal of hydrophobic organic compounds from airstreams

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ABSTRACT

Biofilters are fixed bed bioreactors with immobilized biofilm, which are used for the removal of pollutants from airstreams. Partial coating of the bed packing of a biofilter with an organic non-volatile and non-water miscible solvent before biofilm development is a possible way to improve the performance of the systems for the removal of hydrophobic organic compounds. The heavy solvent enhances the sorption capacity of the biofilter and may improve the rate of pollutant biodegradation. In this research a conceptual model for a dual liquid phase biofilter was developed. Using the model and simulation of the process under different conditions, it was shown that the addition of a solvent to the bed of a biofilter can enhance the biodegradation rate of a hydrophobic pollutant when there is efficient contact between biofilm and heavy solvent layers, and when the process is not reaction limited. The results of simulation moreover showed that the difference between the solubility of the pollutant in the solvent and in biofilm is an important factor that determines the usefulness of heavy solvents in biofilters. When the difference is large the inclusion would be reasonable. The model was calibrated to describe the biofiltration of *n*-hexane in a silicone oil amended biofilter. The trends predicted by the model are in good agreement with the experimental data.

1. Introduction

Biological air treatment systems have been widely under investigation in recent years. These systems are suitable for the treatment of polluted airstreams with high volumetric rates and low pollutant concentrations. Volatile organic compounds as well as inorganic compounds (such as hydrogen sulfide and ammonia) have been treated in the systems successfully. Biological air treatment systems are classified in biofilters, biotrickling filters, and bioscrubbers. In biofilters, the polluted air passes through a packed column containing specific microorganisms immobilized on the surface of the packing particles. Pollutants and oxygen diffuse from the gas phase into the biofilm (thin wet layers of microorganisms on solid surface) and the pollutants are degraded by microorganisms. The bed of biofilters is kept wet by humidification of the entering polluted air and/or intermittent irrigation of the bed. Biotrickling filters are similar to biofilters but a liquid medium is constantly trickled on the packing materials. The trickling medium provides water and minerals to the microbes on the packing particles. In biotrickling filters most of biofilm is covered by the liquid and the pollutants and oxygen diffuse through the liquid into the biofilm. Some biodegradation may also occur by the microbes that are suspended in the liquid medium. Bioscrubbers normally consist of two parts: a scrubber in which the pollutants are absorbed in a liquid, and a bioreactor that receives the pollutant containing liquid from the scrubber. The pollutants are degraded in the bioreactor and the liquid returns to the scrubber [1].

Since biological reactions take place in an aqueous phase, poor solubility of hydrophobic organic compounds in aqueous phases causes poor performance of biological waste air treatment systems for the removal of these compounds compared to hydrophilic ones [2].

Several researchers have suggested inclusion of heavy hydrophobic solvents in biological air treatment systems for improving the transfer rate of hydrophobic pollutants into the aqueous phase. Solvent droplets in a biological air treatment system can mediate the transfer of pollutants from air to the aqueous phase. Although the solvent introduces an additional mass transfer resistance, the high concentration of the pollutants in the solvent and the intimate contact of the solvent with the aqueous phase would result in higher transfer rate of the hydrophobic pollutants into the aqueous phase.

Some researchers have examined the use of heavy solvents in biotrickling filters. van Groenstijin and Lake used a mixture of silicone oil and water as trickling medium for *n*-hexane removal and achieved removal of 80 g/(m^3_{bed} h) that was higher than those

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Nomenclature

A	cross-section area of biofilter (m^2)
A_s	specific surface area of biofilter ($m^2\,m^{-3}$)
C_g	concentration in gas phase ($g\,m^{-3}$)
C_l	concentration in biofilm ($g\,m^{-3}$)
C_s	concentration in solvent ($g\,m^{-3}$)
C_l'	concentration in part of biofilm that is in contact with the solvent layer($g\,m^{-3}$)
C_i	inlet gas concentration ($g\,m^{-3}$)
D	diffusion coefficient of pollutant in biofilm($m^2\,s^{-1}$)
G	gas flow rate ($m^3\,s^{-1}$)
H	biofilter height (m)
k_s	constant in Michealis–Menton relation ($g\,m^{-3}$)
K	mass transfer coefficient between air and the solvent ($m\,s^{-1}$)
m_{gb}	Henry's law constant of the pollutant in gas/biofilm system
m_{gs}	Henry's law constant of the pollutant in gas/solvent system
m_{sb}	Henry's law constant of the pollutant in solvent/biofilm system
t	time (s)
v_m	maximum bioreaction rate ($g\,m^{-3}\,s^{-1}$)
x	position in biofilm depth (m)
z	position in biofilter height (m)

Greek letters

α	fraction of the specific surface area that is covered directly by biofilm
β	fraction of the specific surface area which on the biofilm and the solvent layer overlap
γ	fraction of the specific surface area that is covered with solvent layers
δ	biofilm thickness (m)
ε	porosity of the bed of biofilter
θ	ratio of volume of solvent to the volume of bed
ϕ	Thiele modulus

obtained by other researchers in silicone oil free biotrickling filters [3]. A similar system was used for the removal of a mixture of aromatic compounds from air. Removal efficiency of aromatics in a silicone oil added biotrickling filter was 2.4 folds higher than the removal efficiency in a control biotrickling filter [4]. Arriaga et al. amended the trickling medium of a biotrickling filter with silicone oil and obtained the elimination capacity of 180 g *n*-hexane/(m^3_{bed} h) compared to 110 g *n*-hexane/(m^3_{bed} h) in a control biotrickling filter [5].

Some reports of using heavy solvents in stirred tank bioreactors can be found in the literature. Stirred tank bioreactors can be considered as a special type of bioscrubbers in which both absorption and degradation of the pollutant take place in one vessel. Arriaga et al investigated the effect of silicone oil on *n*-hexane elimination capacity of a stirred tank bioreactor. The silicone oil amended stirred tank bioreactor gave the elimination capacity of 120 g *n*-hexane/($m^3_{reactor}$ h) compared to 50 g *n*-hexane/($m^3_{reactor}$ h) in a control reactor [5]. Davidson and Daugulis demonstrated the usefulness of using a heavy solvent (hexadecane) in a stirred tank bioreactor for the removal of benzene from polluted air. They obtained the removal capacity of 133 g *n*-benzene/($m^3_{reactor}$ h) that was considerably higher than similar systems without a heavy solvent [6]. Kan and Deshusses developed a special type of bioreactor called foamed emulsion bioreactor that was highly efficient in removing toluene from polluted air. They used oleyl alcohol as an immiscible organic phase and a surfactant to help foam formation. Toluene absorbed in the liquid phases through the large surface area provided by foams and was degraded in the aqueous phase by an actively growing microbial culture. The foams collapsed in a defaomer and recycled to the bioreactor. The bioreactor showed the elimination capacity of 202 g toluene/(m^3_{reacor} h) when the inlet concentration was 2.2 $g\,m^{-3}$. The elimination capacity increased to 408 g toluene/(m^3_{reacor} h) when the entering air enriched with oxygen. The elimination capacity in this system was considerably higher than conventional systems [7]. In another work Kan and Deshusses examined the strategies for continuous operation of foamed emulsion bioreactors [8].

Inclusion of heavy organic solvents has been also examined in biofilters. Budwill and Coleman coated peat granules with silicone oil and used it as the bed of a biofilter. Removal efficiency of 66% and elimination capacity of 16 g *n*-hexane/(m^3_{bed} h) were attained against 24% and 8.2 g *n*-hexane/(m^3_{bed} h) in a control biofilter without silicone oil [9]. However, the reported maximum elimination capacity was lower than the results from other researchers that used biofilters without adding silicone oil [10]. Fazaelipoor and Shojaosadati amended silicone oil to a perlite-based biofilter for the removal of *n*-hexane and compared its performance with a control biofilter. The results showed only a slight improvement in the elimination capacity of the silicone oil amended biofilter compared to the control one [11]. In another research Fazaelipoor et al. used a different microbial culture (with higher affinity to *n*-hexane) in another perlite-based biofilter and investigated the effect of silicone oil on the performance of the biofilter. The results showed a considerable improvement in the performance of the oil amended biofilter and it was concluded that the usefulness of amending a heavy organic solvent to a biofilter depends on the bioreaction rate in the biofilter. If the microbial culture in the biofilter has low affinity to a pollutant, amending a heavy solvent might not be useful [12]. Other factors may also influence the usefulness of amending a heavy organic solvent to a biofilter.

Mathematical modeling of two liquid phase biological systems for waste air treatment can improve the insight into the process and help successful application of heavy solvents in the systems. Although many models have been presented for biological waste air treatment systems, only a few of them included the presence of a heavy solvent in the systems. Cesario et al. conducted a theoretical study on the feasibility of using a water immiscible organic solvent for improving the removal efficiency of bioscrubbers and biotrickling filters for hydrophobic pollutants, and concluded that the use of an organic solvent is only advantageous when the solvent shows high affinity for the pollutants, and the specific area for mass transfer between the solvent and water is large enough to compensate for the additional mass transfer resistance introduced by the solvent. Their conclusion was based on the assumption of no biological reaction limitation in the aqueous phase [13]. The bioreaction rate, however, might influence the usefulness of heavy solvents in waste gas biotreatment systems. The effects of different kinetic and mass transfer parameters on the performance of a two liquid phase stirred tank bioreactor have been investigated using a mechanistic model in our previous work [14]. Kan and Deshusses modeled their newly developed system called foamed emulsion bioreactor (mentioned above) in order to understand the basic phenomena involving in the process [15]. In the present study, for the first time, a mechanistic model is developed for the inclusion of a heavy organic solvent in a biofilter. The model is calibrated to describe a set of experimental data. Using the model the usefulness of amending a heavy organic solvent to a biofilter is discussed under different conditions.

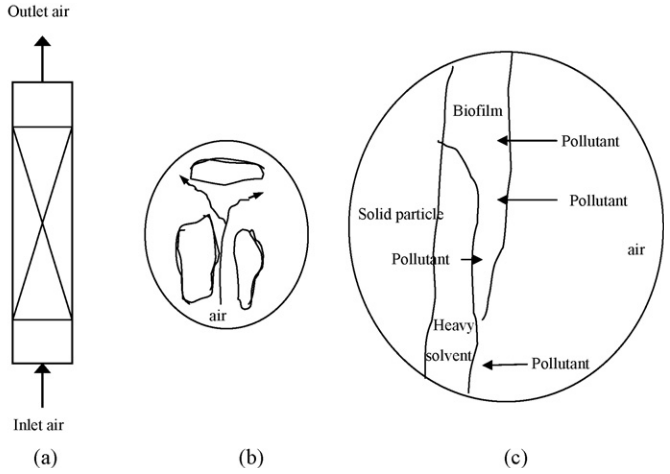

Fig. 1. Schematic of a biofilter (a), close view inside biofilter (b), and close view of the surface of a particle, containing heavy solvent and biofilm (c).

2. Theory

2.1. Model development

Microbes grow on the surface of packing materials and form layers (biofilm) with a complex geometry. However in the biofiltration modeling the biofilm is usually considered as a uniform layer with a fixed thickness. In a heavy solvent containing biofilter, microbes can grow in the vicinity of solvent layers and form a biofilm that may overlap the solvent layers. Fig. 1 shows the schematic of a heavy solvent containing biofilter. Following assumptions were used to derive the governing equations:

1. The process is isothermal and the ideal gas law applies for the gas phase.
2. The gas flow through the bed of biofilter is an ideal plug flow.
3. Biodegradation of the pollutant occurs only in the biofilm.
4. Oxygen is not limited for the process.
5. There is no net biomass accumulation in the biofilter bed.
6. The rate of biodegradation depends on the concentration of the pollutant in biofilm and is expressed by a Michaelis–Menten type relation.
7. The mechanism of mass transfer in biofilm is diffusion.
8. Diffusivity of the pollutant in biofilm is the diffusivity in water corrected by the correlation of Fan et al. [16].
9. The packing material is partially covered with the biofilm. Heavy solvent layers also exist on the surface of the particles. Since before loading in the biofilter, the packing is mixed with solvent, there is the possibility of contact between biofilm and solvent layers. A part of the packing surface is bare.
10. The pollutant concentration at the air/biofilm, air/solvent, and solvent/biofilm interfaces are always in equilibrium as dictated by Henry's law.
11. The rate of mass transfer from the air into the solvent is approximated by a linear driving force model.
12. The biofilm is modeled as a flat plate. This is a reasonable approximation because the thickness of biofilm is much smaller than the diameter of particles.
13. Adsorption of the pollutant in solid particle is negligible.

A differential element is considered along the height of biofilter. The process involves three phases: gas phase, biofilm, and organic solvent. To model the process a mass balance equation should be written for each phase.

2.1.1. Mass balance for the gas phase

The pollutant diffuses from the gas phase into the biofilm and the heavy solvent. Since a part of the biofilm is in contact with the solvent and receives the pollutant from it (besides receiving the pollutant from air, Fig. 1c) the concentration of the pollutant in this part may be different from the rest of biofilm. Consequently the diffusion rate of pollutant to this part would also be different from the rest. So the mass balance equation for the gas phase is

$$\frac{\partial C_g}{\partial t} = -\frac{G}{\varepsilon A}\frac{\partial C_g}{\partial z} - \frac{1-\varepsilon}{\varepsilon}\left[-\alpha A_s D\left(\frac{\partial C_l}{\partial x}\right)_{x=0} - \beta A_s D\left(\frac{\partial C_l'}{\partial x}\right)_{x=0} + \gamma A_s K\left(\frac{C_g}{m_{gs}} - C_s\right)\right] \quad (1)$$

Boundary condition:

$$C_g(0,t) = C_i \quad (2)$$

Initial condition:

$$C_g(z,0) = 0 \quad (3)$$

2.1.2. Mass balance for the biofilm

As mentioned before, a part of biofilm receives pollutant only from air while another part receives pollutant from both the air and the heavy solvent (Fig. 1). For each part we have a mass conservation equation.

Mass balance for the part of biofilm that receives pollutant only from the air:

$$\frac{\partial C_l}{\partial t} = D\frac{\partial^2 C_l}{\partial^2 x} - \frac{v_m C_l}{k_s + C_l} \quad (4)$$

Boundary conditions:

$$C_l(z,0,t) = \frac{C_g(z,t)}{m_{gb}} \quad (5)$$

$$\frac{\partial C_l(z,\delta,t)}{\partial x} = 0 \quad (6)$$

Initial condition:

$$C_l(z,x,0) = 0 \quad (7)$$

Mass balance for the part of biofilm which receives pollutant from both the air and the heavy solvent:

$$\frac{\partial C_l'}{\partial t} = D\frac{\partial^2 C_l'}{\partial x^2} - \frac{v_m C_l'}{k_s + C_l'} \quad (8)$$

Boundary conditions:

$$C_l'(z,0,t) = \frac{C_g(z,t)}{m_{gb}} \quad (9)$$

$$C_l'(z,\delta,t) = \frac{C_s(z,t)}{m_{sb}} \quad (10)$$

Initial condition:

$$C_l'(z,x,0) = 0 \quad (11)$$

2.1.3. Mass balance for the solvent phase

The solvent phase receives pollutant from the air and delivers it to the biofilm so the mass balance equation is

$$\frac{\partial C_s}{\partial t} = \frac{1-\varepsilon}{\theta}\gamma A_s K\left(\frac{C_g}{m_{gs}} - C_s\right) - \frac{1-\varepsilon}{\theta}\beta A_s D\left(\frac{\partial C_l'}{\partial x}\right)_{x=\delta} \quad (12)$$

Initial condition:

$$C_s(z,0) = 0 \quad (13)$$

Table 1
Parameters used in the model

Parameter	Value	Symbol and unit	Reference
Height	0.4	H (m)	[12]
Cross-section area	0.002	A (m^2)	[12]
Flow rate	0.4	G (L min^{-1})	[12]
Porosity	0.41	ε	[12]
Specific surface area of bed particles	1200	A_s (m^2 m^{-3})	[12]
Diffusion coefficient of hexane in biofilm	5.3×10^{-10}	D (m^2 s^{-1})	Calculated for water and corrected by Fan et al. correlation [16]
Maximum bioreaction rate	4.6	v_m (g m^{-3} s^{-1})	Chosen to fit experimental data
Constant in Michaelis–Menten equation	0.152	k_s (g m^{-3})	Chosen to fit experimental data
Biofilm thickness	1.5×10^{-5}	δ (m)	Chosen to fit experimental data
Henry's law constant for hexane in air/biofilm system (C_g/C_l)	35	m_{gb}	The datum for air/water system corrected by the factor 0.5
Henry's law constant for hexane in air/solvent system (C_g/C_s)	4.0×10^{-3}	m_{gs}	Measured using the method in [19]
Henry's law constant for hexane in solvent/biofilm system (C_s/C_l')	8.75×10^3	m_{sb}	$m_{sb} = m_{gb}/m_{gs}$
Percentage of the surface of particles covered by biofilm	70	α	Chosen to fit experimental data
Mass transfer coefficient of hexane between air and solvent	1.2×10^{-4}	K (m s^{-1})	Chosen to fit experimental data
Solvent volume/bed volume	6.25×10^{-2}	θ	[12]
Percentage of the surface of particles covered by biofilm and solvent (overlapped)	20	β	Chosen to fit experimental data
Percentage of the surface of particles covered by solvent	20	γ	Chosen to fit experimental data

Note that it is supposed that at each position along the height of biofilter there is no concentration gradient in the heavy solvent phase.

The set of equations was solved using a finite difference method.

3. Results and discussions

3.1. Description of experimental data using the model

The model was used to predict the performance of a silicone oil amended biofilter for the removal of *n*-hexane from a polluted air stream. The biofilter was a glass column with the height of 50 cm and the inner diameter of 5 cm. The column was packed with 200 g perlite (2 mm < particle size < 4 mm). The particles had been partially coated with 50 g silicone oil before packing in the column. The column was inoculated with an *n*-hexane degrading bacterial culture. A mineral solution was added to the column intermittently to keep the bed wet and provide nutrients to microbes. A polluted air stream with the constant flow rate of 400 mL/min entered the column. A similar biofilter (free of silicone oil) was used as a control. Data were collected under different inlet concentrations. Details on experimental work can be found elsewhere [12]. Table 1 presents the list of the parameters that have been used in the model. Some of the parameters were taken from literature, some measured or calculated, and some were fitted using the model equations and some specific experimental data. To describe the experimental data for the control biofilter, the model was modified to be suitable for it (all parameters were the same with the exceptions $\gamma = 0$ and $\beta = 0$). Fig. 2 shows elimination capacity versus mass loading under steady state conditions. The figure demonstrates the usefulness of silicone oil in a biofilter experimentally. The experimental data are reasonably in good agreement with the model prediction. Fig. 3 presents some experimental data from the same biofiltration system when a step increase at the inlet concentration occurs. After the change at the inlet concentration a rapid response can be seen at the outlet of the oil free biofilter whereas the response at the outlet of the oil amended biofilter occurs after longer times. This demonstrates the ability of the oil amended biofilter to damp fluctuations at the inlet concentration. The model in this case also describes the process well. Figs. 4 and 5 show the responses of the biofilters to a step decrease and a shock change at the inlet concentration respectively. In these two cases the model describes the trends well but the deviation from experimental data is rather large. The deviation can be attributed to changes in some model parameters during biofiltration. Parameters such as the degree of biofilm/silicone oil contact, porosity, and the amount of silicone oil in the biofilter (the oil wastes during mineral medium addition to the bed) are prone to change. Since these parameters were assumed to be constant during biofiltration and the experimental data were collected at

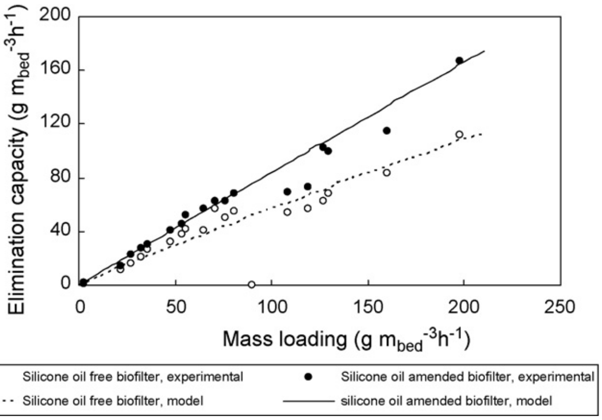

Fig. 2. Description of experimental data with the model (mass loading versus elimination capacity under steady state conditions).

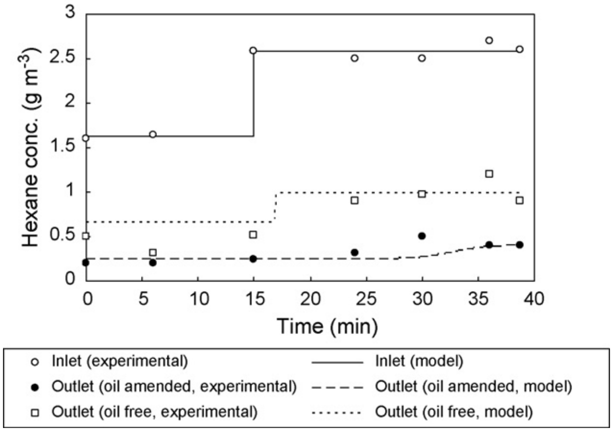

Fig. 3. Description of experimental data with the model (step increase at inlet concentration).

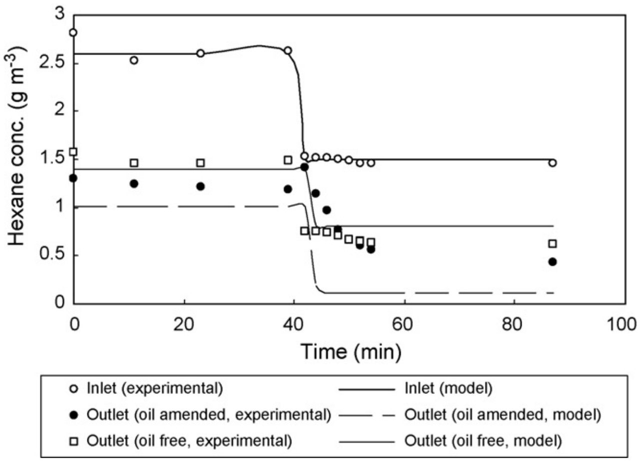

Fig. 4. Description of experimental data with the model (step decrease at inlet concentration).

different times, the consequence is the deviation of the model predictions from experimental data. This suggests that the results of the model should be used with caution in practical situations. In spite of this, since the model predicts the trends quite well, it is a powerful tool in analysis of dual liquid phase biofilters.

3.2. Analysis of dual liquid phase biofiltration using the model

In this part, using the model the effects of different parameters on the performance of a solvent amended biofilter are simulated. The parameters used in simulation are generally the same parameters in Table 1 and in each case the parameters that are different from the ones in Table 1 are mentioned under the figure. The biofilm surface area and all other geometrical and operational parameters are assumed to be equal for the solvent amended biofilter and the control one. The only difference between the two is the absence of the heavy solvent in the control biofilter.

3.2.1. The effect of heavy organic solvent on the biofilter performance with the assumption of no mass transfer between solvent and biofilm

Fig. 6 compares the performance of a solvent amended biofilter with a solvent free biofilter. It is supposed that there is no contact between the biofilm and solvent ($\beta = 0$). As it can be seen in the figure, in this case the solvent does not improve the elimination capacity of biofilter but enhances the sorption capacity of it. Fig. 7 shows response of the biofilters to a sudden increase at the concentration of the entering air. The solvent amended biofilter can damp the sudden changes at inlet concentration though there is little difference between the elimination capacities of the biofilters under steady state conditions. The ability of a solvent amended biofilter to damp fluctuations at entering concentrations has been shown experimentally in our previous work [12]. So amending a heavy solvent to a biofilter has the advantage of increasing the biofilter sorption capacity even if it cannot increase the biodegradation rate.

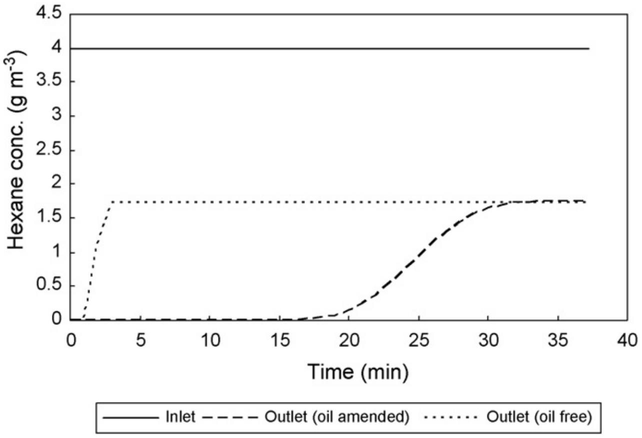

Fig. 6. Comparison between performances of silicone oil amended and silicone oil free biofilters (no mass transfer between solvent and biofilm).

3.2.2. The effect of heavy solvent on the biofilter performance with the assumption of mass transfer between solvent and biofilm

It is clear that the usefulness of a heavy solvent in the biofilter depends on the possibility of mass transfer between the heavy solvent and biofilm. Therefore the solvent should be spread on the surface of the particles in a way that the contact between the solvent and the biofilm becomes possible. Partial coating of the surface of particles with the heavy solvent before loading in the biofilter seems to be a good way. After loading and inoculation, microbes would have the opportunity to grow near the solvent layers and be in contact with the solvent. Fig. 8 compares the performance of a solvent amended biofilter with a solvent free biofilter with the assumption of mass transfer between the liquid phases. In this

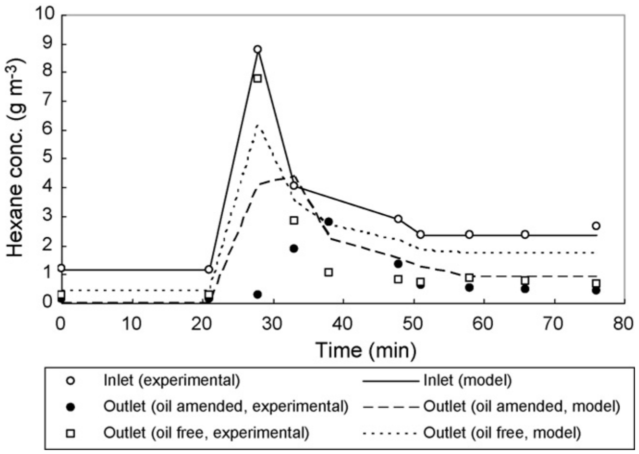

Fig. 5. Description of experimental data with the model (a shock increase at inlet concentration).

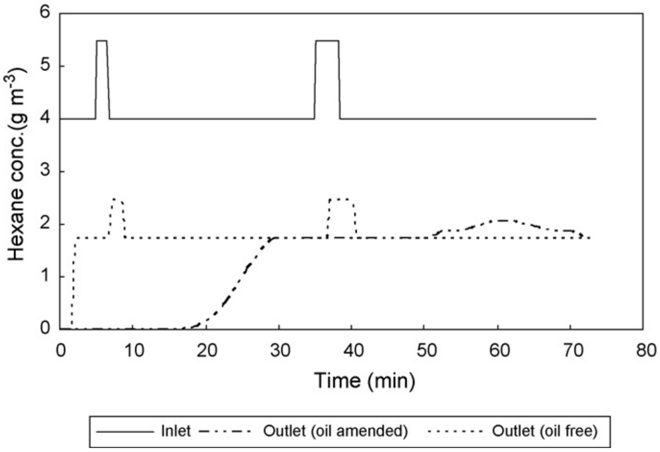

Fig. 7. Responses of silicone oil amended and silicone oil free biofilters to sudden changes at the inlet concentration (no mass transfer between solvent and biofilm).

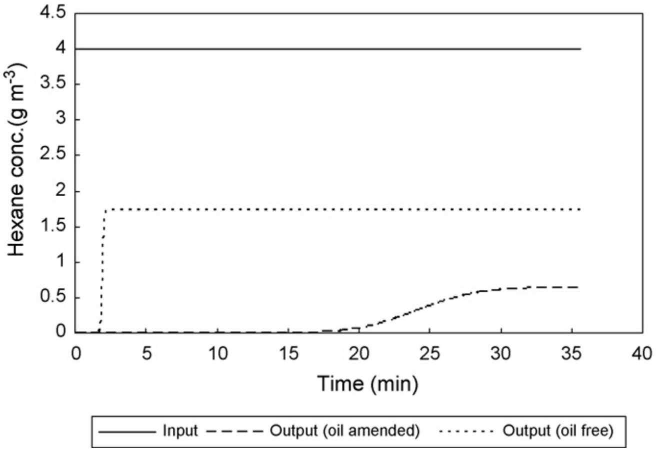

Fig. 8. Comparison between performances of silicone oil amended and silicone oil free biofilters (mass transfer occurs between solvent and biofilm).

case in addition to the increase in the sorption capacity, the removal capacity of the solvent amended biofilter is better than the control biofilter under steady state condition.

3.2.3. *Heavy solvent and bioreaction limitation in a biofilter*

Amending a solvent to the bed of a biofilter is useful when the process is not limited by the rate of reaction. Thiele modulus is a dimensionless group involving kinetic and diffusion parameters and its value depends on the bioreaction and diffusion rates. For a flat geometry and a Michaelis–Menten type expression for bioreaction rate, Thiele modulus is described as [17]:

$$\phi = \frac{\delta}{\sqrt{2}}\sqrt{\frac{v_{\mathrm{m}}}{DC_{\mathrm{l}}}}\left(\frac{1}{1+(k_{\mathrm{s}}/C_{\mathrm{l}})}\right)\left[1+\frac{k_{\mathrm{s}}}{C_{\mathrm{l}}}\ln\left(\frac{k_{\mathrm{s}}/C_{\mathrm{l}}}{1+(k_{\mathrm{s}}/C_{\mathrm{l}})}\right)\right]^{-1/2} \qquad (14)$$

Higher Thiele Moduli means higher bioreaction rate compared to diffusion rate. Fig. 9 compares the difference in performance between a heavy solvent amended biofilter and a control biofilter under a high and a low Thiele Modulus. As the figure shows under steady state conditions the difference in biofilter performances would be significant if the value of Thiele modulus is high. Under low Thiele moduli (that means the process is limited by bioreaction rate) the heavy solvent does not improve the biotic removal capacity of a biofilter. This case can explain some unsuccessful applications of heavy organic solvents in biofilters.

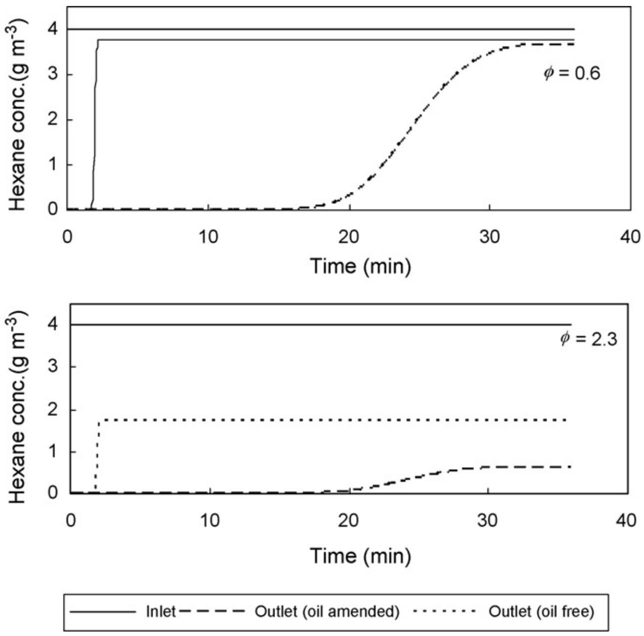

Fig. 9. Comparison between performances of silicone oil amended and silicone oil free biofilters under a low (above) and a high (below) Thiele modulus (ϕ).

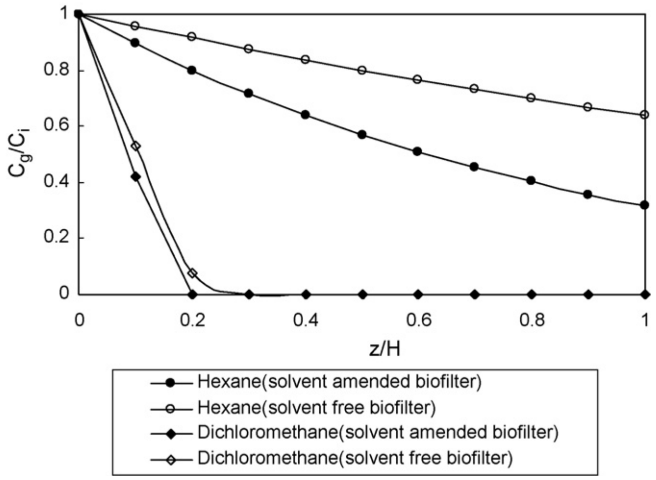

Fig. 10. Comparison between profiles of dichloromethane ($m_{\mathrm{gb}}/m_{\mathrm{gs}} = 17$) and hexane ($m_{\mathrm{gb}}/m_{\mathrm{gs}} = 5916$) concentrations along the height of solvent amended and solvent free biofilters (biodegradation rate assumed to be equal).

3.2.4. *The ratio of solubility of pollutant in solvent to solubility in biofilm*

The ratio of solubility of pollutant in the heavy solvent to solubility in biofilm ($m_{\mathrm{gb}}/m_{\mathrm{gs}}$) is an important factor that determines the usefulness of amending a solvent to a biofilter. To demonstrate this fact, the performance of a dodecene amended biofilter for the removal of *n*-hexane and dichloromethane was simulated. (The solvent changed to dodecene since the Henry's law constants for these two pollutants in air/docecene and air/water systems were available in the literature [13]. Dodecene is a suitable heavy solvent to be used in biological air treatment systems [18].) The reaction rates and all other operational parameters are assumed to be equal for both pollutants. For hexane the ratio $m_{\mathrm{gb}}/m_{\mathrm{gs}}$ is 5916 while for dichloromethane this ratio is 17. Fig. 10 shows that for dichloromethane the difference in performance between the heavy solvent amended and heavy solvent free biofilter is small while for hexane the difference is large. So amending a heavy solvent to the bed of a biofilter would be preferable for the removal of highly hydrophobic compounds.

4. Conclusion

The mechanistic model presented here is a useful tool for evaluating the usefulness of amending a heavy organic solvent to a biofilter. The model shows amending a heavy solvent to a biofilter is useful in biodegradation enhancement when there is sufficient contact between biofilm and solvent layers and when the process is not reaction limited. The model also shows that the inclusion of a heavy organic solvent to a biofilter enhances the sorption capacity of the biofilter and is useful in damping shock changes at the inlet concentration. The difference in the solubility of the pollutant in solvent and aqueous phase is an important factor that determines the usefulness of the solvent in the biofilter. If the difference is large, application of the solvent would be justifiable.

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