

# A model for treating polluted air streams in a continuous two liquid phase stirred tank bioreactor

Mohammad Hassan Fazaelpoor\*

*Chemical Engineering Department, Faculty of Engineering, Shahid Bahonar University of Kerman,  
Jomhuri Avenue, Kerman, Iran*

Received 7 December 2006; received in revised form 26 February 2007; accepted 28 February 2007  
Available online 3 March 2007

## Abstract

Biological air treatment systems have been widely under investigation in recent years. Inclusion of non-biodegradable organic solvents to these systems is a way to improve the biotic removal capacity of the systems. In this article the process of absorption and biodegradation of a hydrophobic organic compound in a two liquid phase stirred tank bioreactor has been modeled. Using the model it has been shown that the inclusion of an organic solvent is advantageous if certain conditions are met. Some simulation examples showed that the usefulness of adding an organic solvent to the system depends on kinetic parameters of biological reactions and mass transfer coefficients of pollutants and oxygen between the air and liquid phases. Since different factors influence the process, the usefulness of including an organic solvent to the system should be checked in each special case. The simple model presented in this article can help the prediction of the effect of amending a solvent to the bioreactor under a set of given conditions.

© 2007 Elsevier B.V. All rights reserved.

*Keywords:* Stirred tank bioreactor; Non-biodegradable organic solvent; Hydrophobic organic compound; Biotic removal

## 1. Introduction

Biological waste air treatment systems have been widely under investigation in recent years. These systems that use naturally occurring microorganisms to degrade air pollutants, are classified in biofilters, biotrickling filters, and bioscrubbers. Biofilters are fixed bed columns with immobilized biofilm on packing particles. A polluted air stream passes through the bed and the pollutants and oxygen diffuse into the biofilm and are degraded by microorganisms. The bed is kept wet by intermittent irrigation or humidifying the entering air stream. In biotrickling filters, a liquid solution is being constantly circulated through the bed and the bed particles are surrounded by a liquid film. The pollutants diffuse into the liquid medium and from there into the biofilm on the particles, where they are degraded by microorganisms. The pollutants are also degraded partly by suspended microorganisms in the liquid medium. A bioscrubber consist of an absorber and a bioreactor. The pollutants are absorbed in the

absorber and degraded in the bioreactor. Although all biological waste air treatment systems have common basic features, they have some advantages and disadvantages when compared to each other [1].

Since all biological reactions take place in the presence of water, the effectiveness of the biological processes for treatment of hydrophobic compounds is relatively poor [2]. Inclusion of a heavy organic solvent such as silicone oil in a biological air treatment system can improve the net transfer rate of hydrophobic compounds from air into the aqueous phase of the system. Solvent droplets in a biological air treatment system can mediate the transfer of the pollutants from the air to the aqueous phase and improve the performance of the system. Cesario et al. [3] conducted a theoretical study on the feasibility of using a water immiscible organic solvent for improving the efficiency of bioscrubbers and biotrickling filters, and based on the difference between the calculated volumes of solvent amended bioreactors and the control solvent free bioreactors concluded that the use of an organic solvent would be advantageous only if the solvent has high affinity for the pollutants, and also if the specific area for mass transfer between the solvent and water is large enough to compensate for the additional transfer resistance, introduced

\* Tel.: +98 341 2118298.

E-mail address: [fazaelpoor@yahoo.com](mailto:fazaelpoor@yahoo.com).

by the solvent. They, however, assumed an instant biological reaction in the aqueous phase and ignored the effect of kinetic parameters of bioreactions on the process. Other researchers have examined the use of heavy solvents in biotrickling filters. van Groenstijn and Lake [4] used a mixture of silicone oil and water as the trickling medium in a biotrickling filter and obtained the elimination capacity of  $80 \text{ g m}_{\text{bed}}^{-3} \text{ h}^{-1}$  for hexane that was higher than those obtained by other researchers in oil free biotrickling filters. A similar system was used for removal of a mixture of aromatic compounds from an air stream. The elimination capacity for the aromatics in a silicone oil amended biotrickling filter was 2.4 folds higher than the elimination capacity in a control biotrickling filter [5]. Fazelipour et al. [6] showed that the inclusion of silicone oil in the bed of a biofilter could enhance the *n*-hexane removal efficiency of the biofilter considerably compared to a control oil free biofilter.

Inclusion of heavy organic solvents in biological air treatment systems can also be useful for the removal of hydrophilic compounds from air streams. High concentrations of many organic pollutants have inhibitory effects on biological reactions and if there is an inert heavy organic solvent in the system, the pollutant would partition between the organic and the aqueous phases and the concentration of the pollutant in the aqueous phase would be under control.

The organic solvent should be immiscible with water, non-toxic and non-biodegradable by the employed microorganism(s), as well as being cheap, non-toxic to human, and possessing low volatility [7].

Although it is generally assumed that the inclusion of a heavy organic solvent in biological air treatment systems is useful for the removal of hydrophobic and/or toxic pollutants, regardless of the difficulties that may arise in practical use of the solvents, they may not be useful in all cases. That is because there are many factors that influence the effectiveness of a biological air treatment system, and in analyzing the usefulness of amending heavy organic solvents in biological air treatment systems, all of the factors should be taken into account.

Many fundamental models have been developed for biological air treatment systems, but few of them considered the inclusion of a heavy organic solvent in the system [8]. Our aim here is to develop a mechanistic model for a two liquid phase stirred tank bioreactor to be able to predict the conditions under which the inclusion of a solvent is advantageous compared to an ordinary one liquid phase bioreactor.

## 2. Model development

Fig. 1 shows a schematic of the system. A mixture of aqueous–organic phases flows into the bioreactor continuously. The polluted air stream is dispersed in the liquid medium. Oxygen and the pollutant diffuse into the liquid medium and the pollutant is degraded in the aqueous phase. The effluent liquid medium from the bioreactor separates into aqueous and organic phases and the organic phase recycles to the bioreactor. The treated air exits the bioreactor at the top. To model the process the following assumptions have been made:

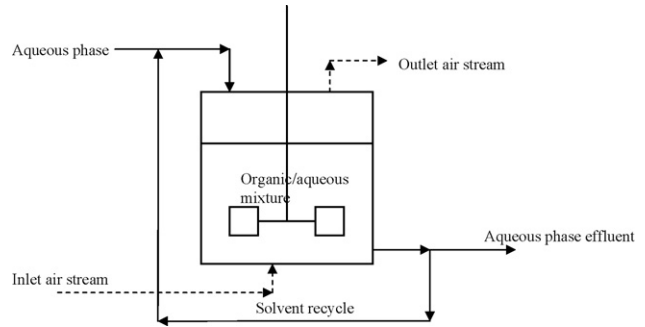


Fig. 1. Schematic of a continuous two liquid phase stirred tank bioreactor for air treatment.

1. The volumes of the two liquid phases are constant in the bioreactor.
2. All phases in the bioreactor are perfectly mixed.
3. There is no mass transfer resistance at the air/aqueous, air/organic, and aqueous/organic interfaces.
4. The oil droplets are homogeneously distributed in the aqueous phase.
5. Oxygen and the pollutant are the only limiting factors for the biological reaction and all other required elements exist in excess.
6. There is a linear driving force for the mass transfer between the gas phase and the liquid phases. There is also a linear driving force for the mass transfer between the aqueous and organic phases.
7. A double substrate Haldane type equation is used for the specific growth rate of the microorganism.
8. The distribution of the pollutant/oxygen between the phases follows the Henry's law.

Based on the above assumptions the governing equations of the process are obtained as below:

- a. Mass balance for the reactants (oxygen and the pollutant) in the gas phase;

$$\frac{dC_i^g}{dt} = D_g(C_{i1}^g - C_i^g) - \frac{K_i^{ga} \varepsilon_a}{\varepsilon_g} \left( \frac{C_i^g}{m_i^{ga}} - C_i^a \right) - \frac{K_i^{gs} \varepsilon_s}{\varepsilon_g} \left( \frac{C_i^g}{m_i^{gs}} - C_i^s \right), \quad C_i^g(0) = C_{i0}^g \quad (1)$$

where *i* stands for the both of the reactants (the pollutant and oxygen),  $C_i^g$  ( $\text{g m}^{-3}$ ) represents the reactant concentration in the gas phase, *t* (s) represents time,  $D_g$  ( $\text{s}^{-1}$ ) is the ratio of the inlet air flow rate ( $Q_g$ ) to the volume of the air in the bioreactor ( $V_g$ ),  $C_{i1}^g$  ( $\text{g m}^{-3}$ ) is the reactant concentration in the inlet air stream,  $K_i^{ga}$  ( $\text{s}^{-1}$ ) is the overall volumetric mass transfer coefficient of the reactant between the gas and the aqueous phase,  $\varepsilon_a$ ,  $\varepsilon_g$ ,  $\varepsilon_s$  are the volume fractions of the aqueous, the gas, and the organic phase in the bioreactor respectively,  $m_i^{ga}$  is the Henry's law constant of the reactant for the distribution between the gas phase and the aqueous phase ( $C_i^g/C_i^a$ ),  $C_i^a$  ( $\text{g m}^{-3}$ ) is the reactant concentration in the aqueous phase,  $K_i^{gs}$  ( $\text{s}^{-1}$ ) is the overall volumetric mass trans-

fer coefficient of the reactant between the gas and the organic phase,  $m_i^{gs}$  is the Henry's law constant of the reactant for the distribution between the gas phase and the organic phase ( $C_i^g/C_i^s$ ),  $C_i^s$  ( $\text{g m}^{-3}$ ) is the reactant concentration in the organic phase, and  $C_{i0}^g$  ( $\text{g m}^{-3}$ ) is the initial concentration of the reactant in the gas phase.

b. Mass balance for the reactants in the aqueous phase;

$$\frac{dC_i^a}{dt} = D_a(C_{i1}^a - C_i^a) + K_i^{ga} \left( \frac{C_i^g}{m_i^{ga}} - C_i^a \right) + K_i^{sa} \left( \frac{C_i^s}{m_i^{sa}} - C_i^a \right) - \frac{\mu X}{Y_{X/i}} \quad (2)$$

where;

$$\mu = \frac{\mu_{\max} C_p^a C_O^a}{(k_p + C_p^a + C_p^{a2}/K_I)(k_O + C_O^a)}, \quad C_i^a(0) = C_{i0}^a \quad (3)$$

where  $D_a$  ( $\text{s}^{-1}$ ) is the ratio of the inlet aqueous flow rate to the volume of the aqueous phase in the bioreactor ( $V_a$ ),  $C_{i1}^a$  ( $\text{g m}^{-3}$ ) is the reactant concentration in the inlet aqueous stream,  $K_i^{sa}$  ( $\text{s}^{-1}$ ) is the volumetric mass transfer coefficient of reactant between the aqueous and the organic phase,  $m_i^{sa}$  is the distribution coefficient of the reactant between the aqueous and the organic phase ( $C_i^s/C_i^a$ ),  $\mu$  ( $\text{s}^{-1}$ ) is the specific growth rate of the microorganism in the aqueous phase,  $X$  ( $\text{g m}^{-3}$ ) is the biomass concentration in the aqueous phase,  $Y_{X/i}$  ( $\text{g biomass/g reactant}$ ) is the yield of biomass growth on the reactant,  $\mu_{\max}$  ( $\text{s}^{-1}$ ) is the maximum specific growth rate of the microorganism,  $C_p^a$  ( $\text{g m}^{-3}$ ) and  $C_O^a$  ( $\text{g m}^{-3}$ ) are the pollutant and oxygen concentrations in the aqueous phase,  $k_p$  ( $\text{g m}^{-3}$ ) and  $k_O$  ( $\text{g m}^{-3}$ ) are half saturation constants for the pollutant and oxygen,  $K_I$  ( $\text{g m}^{-3}$ ) is the inhibition constant for the pollutant, and  $C_{i0}^a$  ( $\text{g m}^{-3}$ ) is the reactant initial concentration in the aqueous phase.

c. Mass balance for the reactants in the organic phase;

$$\frac{dC_i^s}{dt} = D_s(C_{i1}^s - C_i^s) + K_i^{gs} \left( \frac{C_i^g}{m_i^{gs}} - C_i^s \right) - \frac{K_i^{sa} \varepsilon_a}{\varepsilon_s} \left( \frac{C_i^s}{m_i^{sa}} - C_i^a \right), \quad C_i^s(0) = C_{i0}^s \quad (4)$$

where  $D_s$  ( $\text{s}^{-1}$ ) is the ratio of the inlet organic phase flow rate to the volume of the organic phase in the bioreactor ( $V_s$ ),  $C_{i1}^s$  ( $\text{g m}^{-3}$ ) is the reactant concentration in the inlet organic phase, and  $C_{i0}^s$  ( $\text{g m}^{-3}$ ) is the reactant initial concentration in the organic phase.

d. Mass balance for the biomass in the aqueous phase;

$$\frac{dX}{dt} = \mu X - D_a X, \quad X(0) = X_0 \quad (5)$$

where;

$$\mu = \frac{\mu_{\max} C_p^a C_O^a}{(k_p + C_p^a + C_p^{a2}/K_I)(k_O + C_O^a)}$$

where  $X_0$  ( $\text{g m}^{-3}$ ) is the biomass initial concentration in the aqueous phase.

The equations were transformed to dimensionless forms using the following dimensionless parameters:

$$\begin{aligned} X^* &= \frac{X}{X_0}, & C_i^{g*} &= \frac{C_i^g}{C_{i1}^g}, & C_i^{a*} &= m_i^{sa} \frac{C_i^a}{C_{i1}^g}, \\ C_i^{s*} &= m_i^{sa} \frac{C_i^s}{C_{i1}^g}, & k_p^* &= \frac{k_p}{C_{i1}^g}, & k_O^* &= \frac{k_O}{C_{i1}^g}, \\ K_I^* &= \frac{K_I}{C_{i1}^g}, & t^* &= \frac{t}{k}, & p_1 &= \frac{\mu_{\max}}{k}, \\ p_2 &= \frac{D_a}{k}, & p_{3i} &= \frac{K_i^{ga} \varepsilon_a}{k \varepsilon_g}, & p_{4i} &= \frac{K_i^{gs} \varepsilon_s}{k \varepsilon_g}, \\ p_5 &= \frac{D_s}{k}, & p_{6i} &= \frac{K_i^{ga}}{k}, & p_{7i} &= \frac{K_i^{sa}}{k}, \\ p_{8i} &= \frac{X_0 m_i^{sa}}{Y_{X/i} C_{i1}^g}, & p_{9i} &= \frac{K_i^{gs}}{k}, & p_{10i} &= \frac{\varepsilon_a K_i^{sa}}{\varepsilon_s k}, \\ p_{11} &= \frac{D_s}{k} \end{aligned}$$

where;

$$k = \frac{K_p^{ga} K_p^{gs}}{K_p^{sa}}$$

a.

$$\begin{aligned} \frac{dC_i^{g*}}{dt^*} &= p_5(1 - C_i^{g*}) - p_{3i} \left( \frac{C_i^{g*}}{m_i^{ga}} - \frac{C_i^{a*}}{m_i^{sa}} \right) \\ &\quad - p_{4i} \left( \frac{C_i^{g*}}{m_i^{gs}} - \frac{C_i^{s*}}{m_i^{sa}} \right), \quad C_i^{g*}(0) = \frac{C_{i0}^g}{C_{i1}^g} \quad (6) \end{aligned}$$

b.

$$\begin{aligned} \frac{dC_i^{a*}}{dt^*} &= p_2 \left( \frac{m_i^{sa} C_{i1}^a}{C_{i1}^g} - C_i^{a*} \right) + p_{6i} \left( \frac{m_i^{sa} C_i^{g*}}{m_i^{ga}} - C_i^{a*} \right) \\ &\quad + p_{7i} \left( \frac{C_i^{s*}}{m_i^{sa}} - C_i^{a*} \right) - p_{8i} \mu^* X^*, \\ C_i^{a*}(0) &= \frac{m_i^{sa} C_{i0}^a}{C_{i1}^g} \quad (7) \end{aligned}$$

c.

$$\begin{aligned} \frac{dC_i^{s*}}{dt^*} &= p_{11} \left( \frac{m_i^{sa} C_{i1}^s}{C_{i1}^g} - C_i^{s*} \right) + p_{9i} \left( \frac{m_i^{sa} C_i^{g*}}{m_i^{gs}} - C_i^{s*} \right) \\ &\quad - p_{10i} \left( \frac{C_i^{s*}}{m_i^{sa}} - C_i^{a*} \right), \\ C_i^{s*}(0) &= \frac{m_i^{sa} C_{i0}^s}{C_{i1}^g} \quad (8) \end{aligned}$$

$$d. \frac{dX^*}{dt^*} = \mu^* X^* - p_2 X^*, \quad X^*(0) = 1 \quad (9)$$

where;

$$\mu^* = \frac{p_1 C_p^{a*} C_O^{a*}}{(m_p^{sa} k_p^* + C_p^{a*} + C_p^{a*2} / m_p^{sa} k_I^*)(m_O^{sa} k_O^* + C_O^{a*})} \quad (10)$$

This set of initial value differential equations was solved using the fourth order Runge–Kutta method.

### 3. Simulation of the process for a model pollutant

To demonstrate the conditions under which a solvent is useful, toluene was selected as a model pollutant and silicone oil as a model solvent. Toluene has widespread usage in chemical industries and poses air pollution problems due to its volatility. Silicone oil is a non-biodegradable hydrophobic solvent [9].

The data in Table 1 have been used to simulate the removal of toluene from a polluted air stream. Additional data or the data different from Table 1 are under each figure. The operational data (volume of the phases, mass transfer coefficients and biokinetic parameters) are not from any specific operations and have been chosen arbitrarily. It should be noted that these data are in the range of the data that have been reported in the literatures [10–16]. In all simulation cases presented here, it is assumed that the pollutant and oxygen concentrations in the organic phase do not change along the recycle path (so the first term in 4 and 8 can be deleted).

Fig. 2a and b compare the performance of a solvent amended bioreactor with a control bioreactor (in this paper in all cases when a solvent amended bioreactor is compared with a solvent free bioreactor, the only difference between the two bioreactors is that in the solvent free bioreactor the volume of solvent is replaced by an equal volume of the aqueous phase). It can be seen that when the value of  $k_p^*$  is high, the sol-

Table 1

Parameters used in the simulation of the process in the two liquid phase stirred tank bioreactor

Parameter	Value	Unit
$V_a$	0.4	$m^3$
$V_s$	0.2	$m^3$
$V_g$	0.2	$m^3$
$Q_g$	0.02	$m^3 s^{-1}$
$\mu_{max}$	$2.4 \times 10^{-4}$	$s^{-1}$
$k_p$	1	$g m^{-3}$
$K_I$	0.1	$g m^{-3}$
$Y_{X/p}$	1	$g \text{ biomass/g pollutant}$
$Y_{X/O}$	0.5	$g \text{ biomass/g oxygen}$
$m_p^{ga}$	0.27	–
$m_O^{gs}$	34.5	–
$m_p^{gs}$	0.003	–
$m_O^{ga}$	10	–
$K_p^{sa}$	0.012	$s^{-1}$
$K_p^{gs}$	0.012	$s^{-1}$
$K_p^{sa}$	1.2	$s^{-1}$
$K_O^{ga}$	0.012	$s^{-1}$
$K_O^{gs}$	0.012	$s^{-1}$
$K_O^{sa}$	1.2	$s^{-1}$

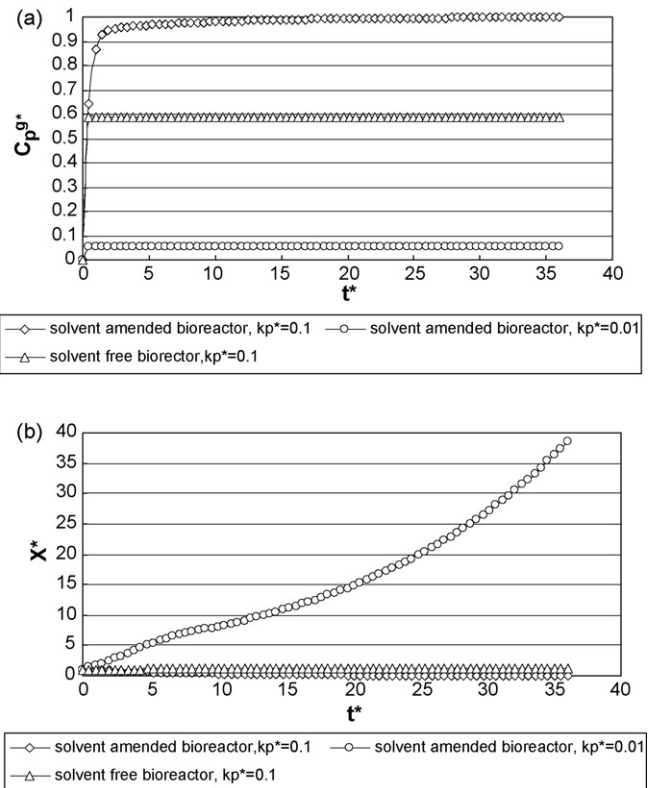


Fig. 2. (a) Comparison of the exit gas concentration from a solvent amended bioreactor under different values of  $k_p^*$  and a control bioreactor. (b) Comparison of the biomass concentration in a solvent amended bioreactor under different values of  $k_p^*$  and a control bioreactor  $C_{pl}^g = 1 g m^{-3}$ ,  $D_a = 2 \times 10^{-5} s^{-1}$ ,  $X_0 = 1000 g m^{-3}$ .

vent has no positive effect on the process as the process approaches the steady state conditions. In fact the solvent may have a negative effect compared to a solvent free bioreactor, because it occupies a fraction of the volume of the bioreactor without improving the biotic removal of the pollutant. It is obvious that existence of an organic solvent with a high affinity toward the pollutant enhances the sorption capacity of the bioreactor, but the solvent enhances the biotic removal of the pollutant only under proper kinetic parameters. Fazelipour et al. [17] amended silicone oil to a perlite based biofilter and showed that it was not much effective compared to an oil free bioreactor, while in another work by improving the reaction kinetics, they showed silicone oil could be effective to improve the biotic removal capacity of a biofilter [6].

The inhibitory effect of the pollutant is another factor that affects the usefulness of the solvent in the bioreactor. Fig. 3a and b compare the performance of a solvent amended bioreactor (under different values of inhibition constant) and a solvent free bioreactor. When the inhibition constant is low, the solvent has no positive effect.

The ratio of the maximum specific growth rate to the mass transfer coefficients between the phases ( $p_1$ ) is also an important factor that determines the usefulness of a heavy solvent in the system. This ratio should be high enough if the sol-

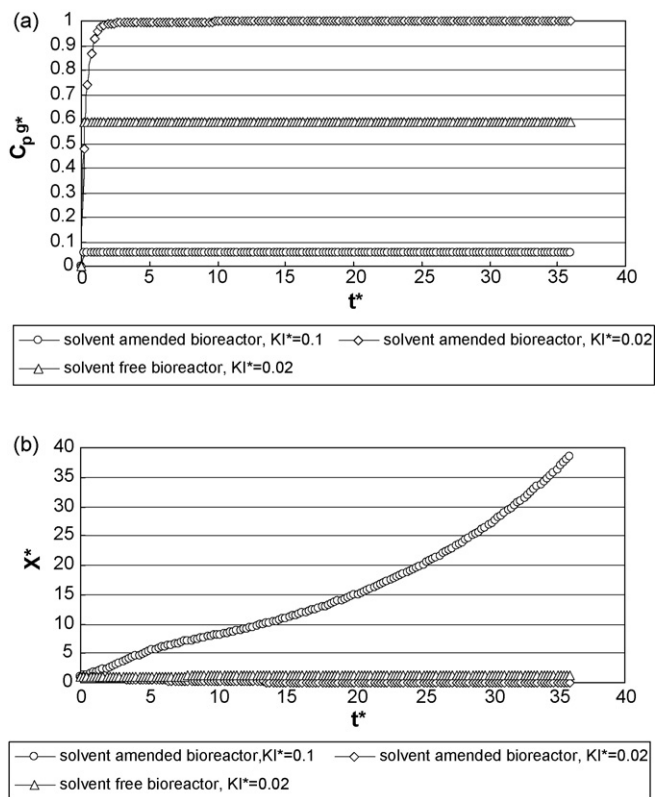


Fig. 3. (a) Comparison of the exit gas concentration from a solvent amended bioreactor under different values of  $k_1^*$  and a control bioreactor. (b) Comparison of biomass concentration in a solvent amended bioreactor under different values of  $k_1^*$  and a control bioreactor  $C_{pl}^g = 1 \text{ g m}^{-3}$ ,  $D_a = 2 \times 10^{-5} \text{ s}^{-1}$ ,  $X_0 = 1000 \text{ g m}^{-3}$ .

vent is to be useful. Fig. 4a and b compare a solvent amended bioreactor under two values of  $p_1$  and a control bioreactor. Under a low value for  $p_1$ , the performance of the solvent amended bioreactor is not considerably better than a solvent free bioreactor. One of the ways of keeping a high  $p_1$ , is increasing  $K_p^{sa}$  by vigorous mixing and/or addition of emulsifiers for adequate dispersion of solvent droplets in the aqueous phase.

In practical situations the concentration of the pollutant in the entering air stream may fluctuate considerably. The concentration may be zero for some periods and may be very high for some other periods. The presence of the solvent can delay the microorganisms to be washed out of the bioreactor during the periods of zero or very low concentration of the pollutant in the entering air stream. This phenomenon is shown in Fig. 5. The concentration of the pollutant in the inlet air stream is the same for the two bioreactors, but under the given operating conditions only the solvent amended bioreactor can prevent the microbial concentration from washing out. The microbes can uptake the pollutant from the solvent during the periods of zero concentration in the inlet air stream.

Some solvents have a good solubility for oxygen and can enhance the overall transfer rate of oxygen from the air to the aqueous phase. This can be useful when the process is under oxygen limitation. Fig. 6a and b compare the performance of

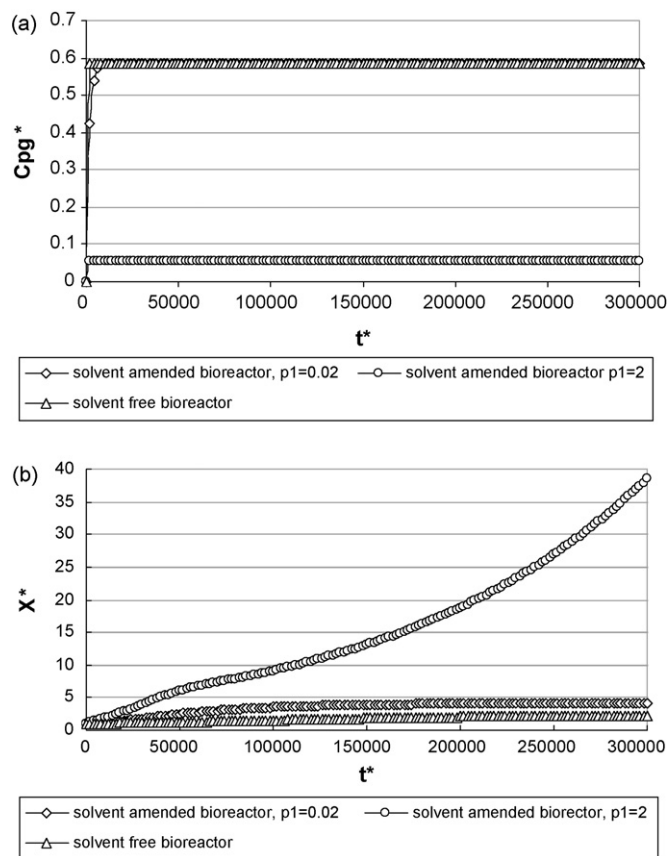


Fig. 4. (a) Comparison of the exit gas concentration from a solvent amended bioreactor under different values of  $p_1$  and a control bioreactor. (b) Comparison of biomass concentration in a solvent amended bioreactor under different values of  $p_1$  and a control bioreactor  $C_{pl}^g = 1 \text{ g m}^{-3}$ ,  $D_a = 2 \times 10^{-5} \text{ s}^{-1}$ ,  $X_0 = 1000 \text{ g m}^{-3}$ .

a solvent amended bioreactor when the oxygen solubility in the solvent is high with a solvent amended bioreactor when the oxygen solubility in the solvent is low. It can be seen that when oxygen is a limiting factor, solvent can be useful in enhancement of biotic removal of the pollutant only if it has good solubility for oxygen.

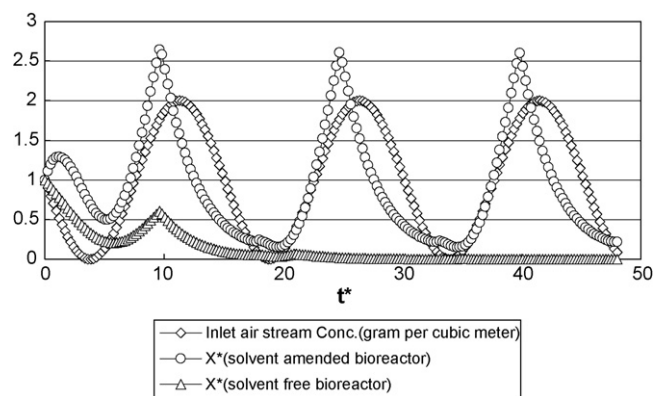


Fig. 5. Variation in biomass concentration in a solvent amended bioreactor and a control bioreactor due to the variation at the concentration of entering air stream.  $D_a = 24.5 \times 10^{-5} \text{ s}^{-1}$ ,  $X_0 = 1000 \text{ g m}^{-3}$ .



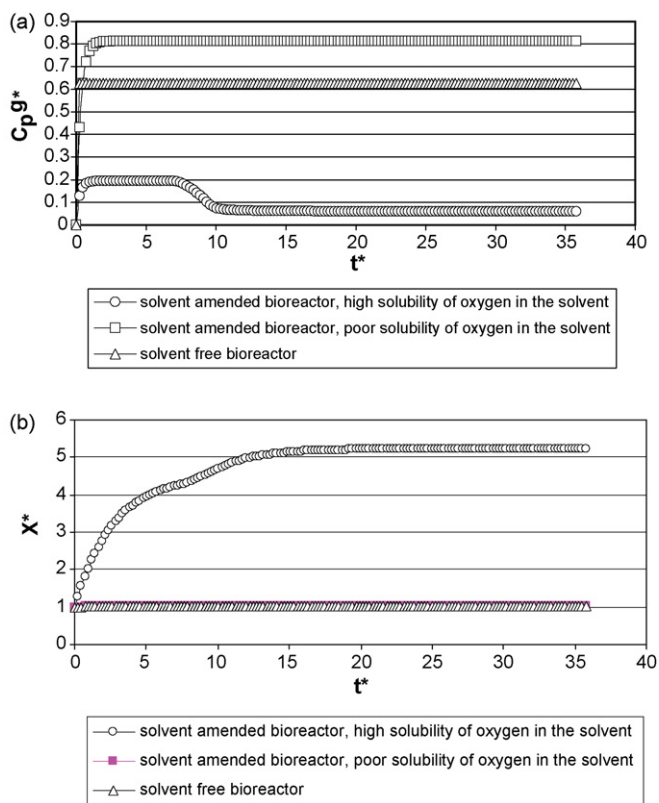


Fig. 6. (a) Comparison of the exit gas concentration from a solvent amended bioreactor under the conditions of high and low solubility of the solvent for the oxygen. (b) Comparison of the biomass concentration in a solvent amended bioreactor under the conditions of high and low solubility of the solvent for oxygen.

#### 4. Conclusion

Addition of a heavy organic solvent to a bioreactor can be useful under certain conditions. The simple model presented in this paper can predict if addition of a solvent to a biological air treatment system is advantageous compared to a solvent free bioreactor under a given set of conditions. Some simulation examples revealed that if  $k_p$  is large (low affinity of microorganisms to the pollutant), and/or  $K_I$  is small (high inhibitory effect of the pollutant), addition of the solvent would have little or negative effect on the improvement of the biotic removal of the pollutant from an air stream. The model also shows that the ratio of maximum specific growth rate to mass transfer coefficients

between the phases ( $p_1$ ) must be high enough if the solvent is to improve the biotic removal of the pollutant. The existence of a solvent is helpful in prevention of the microorganisms from washing out during the periods of zero or low concentration of pollutant at the entering air stream.

#### References

- [1] J.S. Devinny, M.A. Deshusses, T.S. Webster, *Biofiltration for Air Pollution Control*, Lewis Publishers, New York, 1999.
- [2] M. Mohseni, D.G. Allen, *Biofiltration of mixtures of hydrophobic and hydrophilic compounds*, *Chem. Eng. Sci.* 55 (2000) 1545–1558.
- [3] M.T. Cesario, H.H. Beekink, J. Tramper, *Feasibility of using water immiscible organic solvents in biological waste gas treatment*, *Bioprocess Eng.* 12 (1995) 55–63.
- [4] J.W. Van Groenstijin, M.E. Lake, *Elimination of alkanes from off-gases using biotrickling filters containing two liquid phases*, *Environ. Prog.* 3 (1999) 151–154.
- [5] D. Hekmat, D. Vortmeyer, *Biodegradation of poorly water-soluble volatile aromatic compounds from waste air*, *Chem. Eng. Technol.* 4 (2000) 315–318.
- [6] M.H. Fazelipour, S.A. Shojaosadati, E. Vashghani-Farahani, *Two liquid phase biofiltration for removal of *n*-hexane from the polluted air*, *Environ. Eng. Sci.* 23 (6) (2006) 950–955.
- [7] L. Rehmann, A.J. Daugulis, *Biphenyl degradation kinetics by *Burkholderia xenovorans LB400* in two phase partitioning bioreactors*, *Chemosphere* 63 (6) (2006) 972–979.
- [8] J.S. Devinny, J. Ramesh, *A phenomenological review of biofilter models*, *Chem. Eng. J.* 113 (2005) 187–196.
- [9] Ullman's *Encyclopedia of Industrial Chemistry*, vol. A24, *Silicones*, Wiley-VCH, 1985.
- [10] K. Seongyup, M.A. Deshusses, *Development and experimental validation of a conceptual model for biotrickling filtration of  $H_2S$* , *Environ. Prog.* 22 (2) (2003) 119–127.
- [11] D. Kiranmai, A. Jyothirmai, C.V.S. Murty, *Determination of kinetic parameters in fixed film bioreactors: an inverse problem approach*, *Biochem. Eng. J.* 23 (2005) 37–78.
- [12] G. Spigno, M. Zilli, C. Nicoletta, *Mathematical modeling and simulation of phenol degradation in biofilters*, *Biochem. Eng. J.* 19 (2004) 267–275.
- [13] S. Arriaga, et al., *Gaseous hexane biodegradation by *Fusarium solani* in two liquid phase packed bed and stirred tank bioreactor*, *Environ. Sci. Technol.* 40 (2006) 2390–2395.
- [14] J.W. Barton, et al., *Microbial removal of alkanes from dilute gaseous waste streams: kinetics and mass transfer considerations*, *Biotechnol. Prog.* 13 (1997) 814–821.
- [15] I. Iliuta, F. Larachi, *Transient biofiltration aerodynamics and clogging for VOC degradation*, *Chem. Eng. Sci.* 59 (2004) 3293–3302.
- [16] K.F. Reardon, et al., *Biodegradation kinetics of aromatic hydrocarbon mixtures by pure and mixed cultures*, *Environ. Health Perspective* 110 (2002) 1005–1011.
- [17] M.H. Fazelipour, S.A. Shojaosadati, *The effect of silicone oil on biofiltration of hydrophobic compounds*, *Environ. Prog.* 4 (2002) 221–224.