SIMULATION OF BIOTRICKLING FILTERS USING NOVEL FOAMS FOR TREATING ODORS AND VOLATILE COMPOUNDS

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ABSTRACT

Biotrickling filters have been extensively studied for treatment of a wide variety of organic and inorganic contaminants in gaseous emissions from wastewater treatment plants, industrial manufacturing operations and sludge handling systems. Biotreatment offers an economically attractive, ambient temperature and pressure system for treating contaminant emissions than incineration, catalytic oxidation or chemical treatment. The challenge in biotrickling filters is developing a suitable media that can be used to immobilize the active bacteria as biofilms on its surface that delivers high surface area, ability to retain the attached biofilms, low bulk density to reduce the weight of the media beds, and prevent clogging due to biomass growth. Currently, no suitable media that can deliver all of the above characteristics has been developed.

Randomly packed inorganic foam structures, manufactured by a unique process, will be studied as possible support media for biotrickling filters removing Sulfur Reduced Compounds (SRC) from air at different working conditions of concentration and contact time in the filter. Foams offer high surface areas, ability to retain biofilms, low bulk density due to high porosity, and depending on size and geometry, ability to slough-off excess biomass growth to prevent clogging. While polyurethane foams have been studied as biofilter media, they have been used as monoliths, cylindrically wrapped sheets to form a single bed that have been shown to clog due to biomass growth. In this research, computer simulation studies will be conducted to develop a better understanding of gas and liquid hydrodynamics in randomly packed beds using foam structures. Hydrodynamic models will be coupled to biokinetics to model biomass growth and contaminant biodegradation in airstreams containing Hydrogen Sulfide, Methyl Mercaptan, Dymethyl Mercaptan and Carbon Disulfide.

Detailed computer simulation studies have shown that the pore size and porosity of the foam structure as well as the nominal size of the randomly packed foam pieces controls the extent of gas flow through the foam as compared to between the foam pieces. Results of the computer simulation studies and experimental data will be presented to offer some unique insights towards the development of an “optimum” support media for biotrickling filters.

Keywords: Biotrickling filter, solid foam, removal efficiency, model, biofilm growth.

1. Introduction

Emission of Volatile Organic Compounds (VOC) and Sulfur Reduced Compounds (SRC) to the atmosphere, as by-products or off-gases from common industrial processes, is a major concern for environmental regulatory agencies, which are continuously setting tighter air quality standards. In order to minimize the discharge of VOC and SRC, traditional physical and chemical processes such as absorption, adsorption, condensation, incineration and chemical oxidation have been used (Kim *et al*., 1999). However, these processes are often inadequate from an economic standpoint since the concentrations of VOC and SRC in the influent gas streams are generally low, which makes the treatment processes large and expensive.

An alternative to the aforesaid processes, biofiltration, has proven to be an effective technique for the treatment of VOC and SRC at pilot, bench and full scales (Shareefdeen *et al*., 2002; Cohen, 2001; Cárdenas-González *et al*., 1999; Chitwood *et al*., 1999; Cook *et al*., 1999). Biofiltration of VOC and SRC in airstreams is a cost effective removal process, and it is especially suited for polluted gas with low contaminant concentrations. In biofiltration, no downstream separation is needed, the process can be carried out at room pressure and temperature, and there are no chemical costs involved further than the administration of nutrients to the microflora in the system.

Out of the several technical variables upon which the performance of the biofilter depends, such as type and concentration of the species involved, contact mode and time, nutrient solution chemistry, bed pH, moisture content, bacteria nature and carrying media type, it is the latter one that has lately received attention the most by researchers (Moe and Irvin 2000a,b; Shinabe *et al*., 2000; Hirai *et al*., 2001; Delhoménie *et al.*, 2002; Sheridan *et al.*, 2002). Good support media must have high interfacial contact area between the species, low density, high porosity, high water retention capacity, chemical resistance, and appropriate microflora attachment. Although solid open pore polyurethane foams have been reported be the ones that best optimize the overall performance of biofilters treating VOC and SRC (Moe and Irvine, 2000a,b; Moe and Irvine, 2001; Park *et al.*, 2001; Kim *et al*. 2002; Van Groenestijn and Liu, 2002; Benesse and Delebarre, 2003; Gabriel and Deshusses, 2003a,b) no studies have been found in the Literature to deal with the optimization on the design of foams, such as their optimum pore size, porosity, size and shape.

A simplified criterion to optimize the design of solid foams is proposed as follows. While increasing the superficial gas velocity in the system, more gas will flow both within the foam unit and among foam pieces. However, since the interfacial area is several orders of magnitude higher in the internal foam than outside it, the effective contact area between the gas and biofilm supported in the foam struts will increase as well as the contaminant mass transfer. On the other hand, increasing the superficial gas velocity will bring about a reduction in the contact time available for the mass transfer process to occur, depleting the removal efficiency as a consequence. Both effects will counteract at different rates while varying the gas superficial velocity. Thus, there should exist a range of design conditions (i.e. foam and bed porosity, pore size, and superficial gas velocity) under which increasing the gas superficial velocity will actually increase the removal efficiency until a maximum is attained. Provided that the amount of gas flowing within the foam and past the foam can be calculated from models already existing in the Literature, as well as the impact of the residence time on the removal efficiency of the VOC and SRC, an optimum foam design can be estimated.

The aim of this work is to provide the mathematical means to estimate the media configuration under which the performance of a biofilter treating VOC and SRC is optimized. The model compiles correlations for the hydrodynamics in single foams and packed beds, as well as general biokinetics and biomass growth correlations. Gas flow distribution in the reactor and geometric media calculations are also possible by properly combining the aforesaid correlations.

2. Mathematical model

Figure 1 shows the coordinate system used to describe the mass transport within the biofilm and liquid layers in the bioreactor. For a single substrate in a biofilm, Equation (1) describes the mass balance of such substrate as follows:

$$D_f \frac{\partial^2 C_f(x,y)}{\partial x^2} = R_{C_f} \tag{1}$$

$$x = \delta_f\,,\quad C_f(\delta_f, y) = C_l(\delta_f, y) \tag{1a}$$

$$x = 0\,,\qquad \frac{\partial C_f(0,y)}{\partial x} = 0 \tag{1b}$$

In writing Equation (1), the following assumptions are considered: (a) advection is negligible in the biofilm, (b) substrate transport occurs only due to diffusion in the x direction within this control volume, (c) no substrate accumulation or depletion occurs either, (d) the substrate diffusivity in the biofilm is considered to be uniform and constant, (e) no substrate partition takes place at the interface liquid-biofilm, (f) since the biofilm support media is non adsorbant in nature, there is no flux of substrate across it.

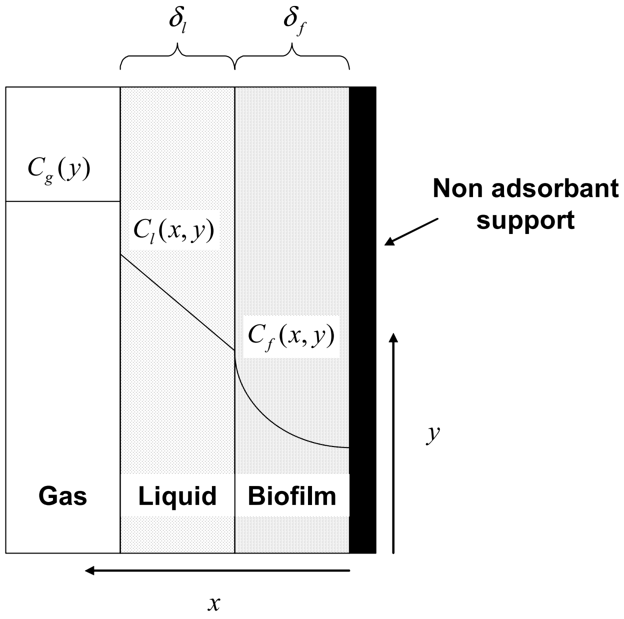

Figure 1. Substrate concentration profile in a biofilter system. Non adsorbant media.

The substrate diffusing into the biofilm is degraded by the microbial consortia, the rate of which can be expressed mathematically as a hyperbolic function as proposed by Monod:

$$R_{C_f} = \frac{kX_f C_f(x,y)}{K_s + C_f(x,y)} \tag{2}$$

Therefore:

$$D_f \frac{\partial^2 C_f(x,y)}{\partial x^2} = \frac{kX_f C_f(x,y)}{K_s + C_f(x,y)} \tag{3}$$

By performing a substrate mass balance in the liquid layer, and recognizing that under steady state conditions the substrate diffusion in the x direction is the only term standing in the balance, the following expression and boundary conditions are derived:

$$\frac{\partial^2 C_l(x,y)}{\partial x^2} = 0 \tag{4}$$

$$x = \delta_f, \qquad C_l(\delta_f, y) = C_f(\delta_f, y) \tag{4a}$$

$$x = \delta_f + \delta_l, \qquad C_l(\delta_f + \delta_l, y) = \frac{1}{H} C_g(\delta_f + \delta_l, y) \tag{4b}$$

The boundary condition described in Equation (4b) accounts for the fact that there exists a substrate partition between the liquid and gas phases, the value of which can be easily obtained by using solubility coefficients from Henry's law. It can be further assumed that there exists complete mixing of the substrate in the gas phase along the x direction. Consequently:

$$C_g(\delta_f + \delta_l, y) = C_g(x > \delta_f + \delta_l, y) \tag{5}$$

The change in the advective flow of substrate along the bed equals the flow of substrate diffusing into the liquid layer from the bulk gas. Thus:

$$-v_g \frac{dC_g(y)}{dy} = A_s J_g(y) \tag{6}$$

From the conservation of mass:

$$A_s J_g(y) = A_s J_l(y) = A_s J_f(\delta_f, y) \tag{7}$$

The substrate diffusive flux in the liquid phase, which is uniform in the x direction, can be expressed in terms of Fick's law:

$$J_l(y) = D_l \frac{\partial C_l(\delta_f + \delta_l, y)}{\partial x} = D_l \frac{\partial C_l(\delta_f, y)}{\partial x} \tag{8}$$

Combining Equations (6) through (8):

$$-v_g \frac{dC_g(y)}{dy} = A_s D_f \frac{\partial C_f(\delta_f, y)}{\partial x} \tag{9}$$

Parvatiyar *et al*. (1996) proposed that:

$$J_g(y) = J_l(y) = J_f(\delta_f, y) = \frac{D_f}{v_g} R_{C_f}\Bigg|_{x=\delta f} \tag{10}$$

Combining Equations (2) and (10):

$$J_g(y) = J_l(y) = \frac{D_f}{v_g} \frac{kX_f C_f(\delta_f, y)}{K_s + C_f(\delta_f, y)} \tag{11}$$

The total substrate flux can also be expressed in terms of a mass transfer coefficient in the liquid phase as follows:

$$J_l(y) = k_l\big(C_l(\delta_f + \delta_l, y) - C_l(\delta_f, y)\big) = k_l\left(\frac{C_g(y)}{H} - C_l(\delta_f, y)\right) \tag{12}$$

Combining Equations (11) and (12):

$$C_g(y) = HC_f(\delta_f, y) + \frac{HD_f}{k_l v_g} \frac{kX_f C_f(\delta_f, y)}{K_s + C_f(\delta_f, y)} \tag{13}$$

Equation (13) can be differentiated and combined with Equations (2) and (7) through (10). The resulting expression can be integrated along the longitudinal direction y to give:

$$\left(HK_s + \frac{D_f kX_f}{k_l v_g}\right)\int_{C_{f,i}}^{C_{f,o}} \frac{dC_f(\delta_f, y)}{C_f(\delta_f, y)} + H\int_{C_{f,i}}^{C_{f,o}} dC_f(\delta_f, y) - \frac{D_f kX_f}{k_l v_g}\int_{C_{f,i}}^{C_{f,o}} \frac{dC_f(\delta_f, y)}{K_s + C_f(\delta_f, y)} =$$

$$= -\int_0^L \frac{A_s D_f kX_f}{v_g^2} dy \tag{14}$$

Equation (14) can be simplified to:

$$E = \frac{C_{f,i} - C_{f,o}}{C_{f,i}} = \frac{A_s D_f kX_f L}{Hv_g^2 C_{f,i}} - \frac{K_s}{C_{f,i}} \ln\left(\frac{C_{f,i}}{C_{f,o}}\right) - \alpha \ln\left(\frac{C_{f,i}}{C_{f,o}}\right) + \alpha \ln\left(\frac{K_s + C_{f,i}}{K_s + C_{f,o}}\right) \tag{15}$$

$$\alpha = \frac{D_f k X_f}{H k_l v_g C_{f,i}} \tag{16}$$

Equation (15) is the removal efficiency for the bioreactor.

Mathematically, the effective specific area can be defined as a weighted average of both the internal and external foam piece specific areas, being the weighting factor equal to the percentage of the total gas flow flowing within and around the bed media. In other words:

$$A_s = \frac{v_f}{v_g}(1-\varepsilon_b)\varepsilon_f A_f + \left(1 - \frac{v_f}{v_g}(1-\varepsilon_b)\right)A_b \tag{17}$$

Richardson *et al*. (2000) provided an expression to calculate the internal foam specific area by assuming the foam to have a tetrakaidecahedral configuration. In order to determine the ratio of the gas flow within the foam to the total gas flow, it is assumed that the gas stream pressure drop within a foam unit equals the gas stream pressure drop around it. Then:

$$\left.\frac{\Delta P}{L}\right|_f = \left.\frac{\Delta P}{L}\right|_b \tag{18}$$

The pressure drop within foam media has been studied previously (Smit and DuPlessis, 1999; Richardson *et al*., 2000; Fourie and DuPlessis, 2002). A modified model proposed by Smit and DuPlessis (1999) was selected based upon experimental data collected in our experiments. The pressure drop predicted by the model of Smit and DuPlessis (1999) is multiplied by a factor of 0.333 to fit the data collected in the lab. The pressure drop around the media can be determined from any correlation used to calculate the pressure drop along a stripping or absorption packed bed. The model of Robbins (1991) was selected since it accounts for the effect of increasing the superficial liquid velocity in the bed.

Equation (18) is a function of the geometrical properties of the foam pieces as well as the hydrodynamic operation conditions of the column. The amount of gas flowing within the foams as opposed to past the foams can be calculated for a set of foam design parameters such as pore size and porosity, and the flows of liquid and gas along the column. The ratio of gas flowing within and past the foam is used therefore to solve Equation (17) and then to compute the removal efficiency as described in Equation (15).

Further, since the foam porosity ε_f decreases due to the biofilm and liquid layer presence, such effects should also be accounted for in the calculations. By assuming that the foam is made up with triangular struts as proposed by Richardson *et al*. (2000), the reduction in the foam porosity and pore size with biofilm and liquid layers can be calculated as:

$$\varepsilon_f = 1-(1-\varepsilon_{f,o})\left[\frac{t_s + 3.464(\delta_f + \delta_l)}{t_s}\right]^2 \tag{19}$$

$$d_p = d_{p,o} - 2(\delta_f + \delta_l) \tag{20}$$

Where (Richardson *et al*., 2000):

$$t_s = 0.971 l \sqrt{1-\varepsilon_{f,o}} \tag{21}$$

$$l = 0.5498 d_{p,o} \frac{1}{1-0.971\sqrt{1-\varepsilon_{f,o}}} \tag{22}$$

The liquid layer thickness can be estimated by applying a momentum balance over a flat surface:

$$\delta_l = \sqrt[3]{\frac{3\mu_l v_l}{A_f \rho_l g}} \tag{23}$$

To estimate the biofilm thickness, the model of Rittmann and McCarty (1978, 1980) is used.

3. Results and discussion

For any given set of kinetic parameters and inlet pollutant concentrations, the removal efficiency of the biofilter is a function solely of the ratio $A_s v_g^{-2}$. This ratio is at the same time a function of the geometric properties of the media and bed, and the gas superficial velocity as described in Equation (17). Figure 2 shows how the removal efficiency of a bioreactor treating Hydrogen Sulfide (H_2S) changes with the ratio $A_s v_g^{-2}$ for a bed whose configuration is described in more detail in Table 1. The parameters F_{pd} and C_2 are a empirical factors that depend on the bed porosity and packing shape, and the amount of liquid flowing within the bed as described by Robbins (1991). The liquid mass transfer coefficient k_l was calculated as the ratio of $D_l \delta_l^{-1}$.

Table 1. Values of transport and kinetic parameters for H_2S and other design parameters (Figures 2 through 6)

Parameter	Figure 2	Figure 3	Figure 4	Figures 5 and 6
k [s^{-1}]	0.0025	-	0.0025	0.003
K_s [$kg\cdot m^{-3}$]	$1.0\cdot10^{-6}$	-	$1.0\cdot10^{-6}$	$5.0\cdot10^{-7}$
b [s^{-1}]	-	-	-	$1.0\cdot10^{-5}$
X_f [$g\cdot m^{-3}$]	50	-	50	50
Y	-	-	-	0.20
D_f [$m^{-2}\cdot s^{-1}$]	$1.0\cdot10^{-9}$	-	$1.0\cdot10^{-9}$	$1.0\cdot10^{-9}$
D_l [$m^{-2}\cdot s^{-1}$]	$1.5\cdot10^{-9}$	-	$1.5\cdot10^{-9}$	$1.5\cdot10^{-9}$
v_l [$m\cdot s^{-1}$]	$2.52\cdot10^{-4}$	$2.52\cdot10^{-4}$	$2.52\cdot10^{-4}$	$2.52\cdot10^{-4}$
C_2	$9.45\cdot10^{-5}$	$9.45\cdot10^{-5}$	$9.45\cdot10^{-5}$	$9.45\cdot10^{-5}$
F_{pd} [ft^{-1}]	75	-	75	70
d_p [μm]	50	100	50	2000
ε_f	0.95	0.95	0.95	0.96
ε_b	0.50	0.50	0.50	0.50
A_b [m^{-1}]	600	600	600	600
L [m]	3.0	-	-	3.0
H	0.416	-	0.416	0.416

As seen in Figure 2, the bed removal efficiency increases monotonically with the ratio $A_s v_g^{-2}$, for which maximizing the latter is the objective sought. When the gas superficial velocity is increased, A_s will increase within the range $A_f \geq A_s \geq A_b$ until reaching the asymptotic value of A_f. This is true since the faster the gas flows through the bed, the more gas flows both within the foam as well as around it. However, the internal specific area within the foam, A_f, is several orders of magnitude higher than that of the external foam piece, A_b, for which the contact area between the biofilm and gas is maximized. If the rate at which the effective specific area increases is faster than the rate at which the square of the superficial gas velocity does, then the relationship $A_s v_g^{-2}$ increases and improved substrate removal can be attained. Eventually, a plateau is reached at a maximum gas superficial velocity above which almost all gas is flowing within the foam, and the effective specific area of the media equals that of the internal foam and remains the same for higher velocities. The relationship $A_s v_g^{-2}$ starts to decrease after this point, though, and a reduction in removal efficiency with decreasing residence time is expected. Figure 3 shows the effect of increasing the superficial gas velocity v_g on the relationship $A_s v_g^{-2}$ as described previously.

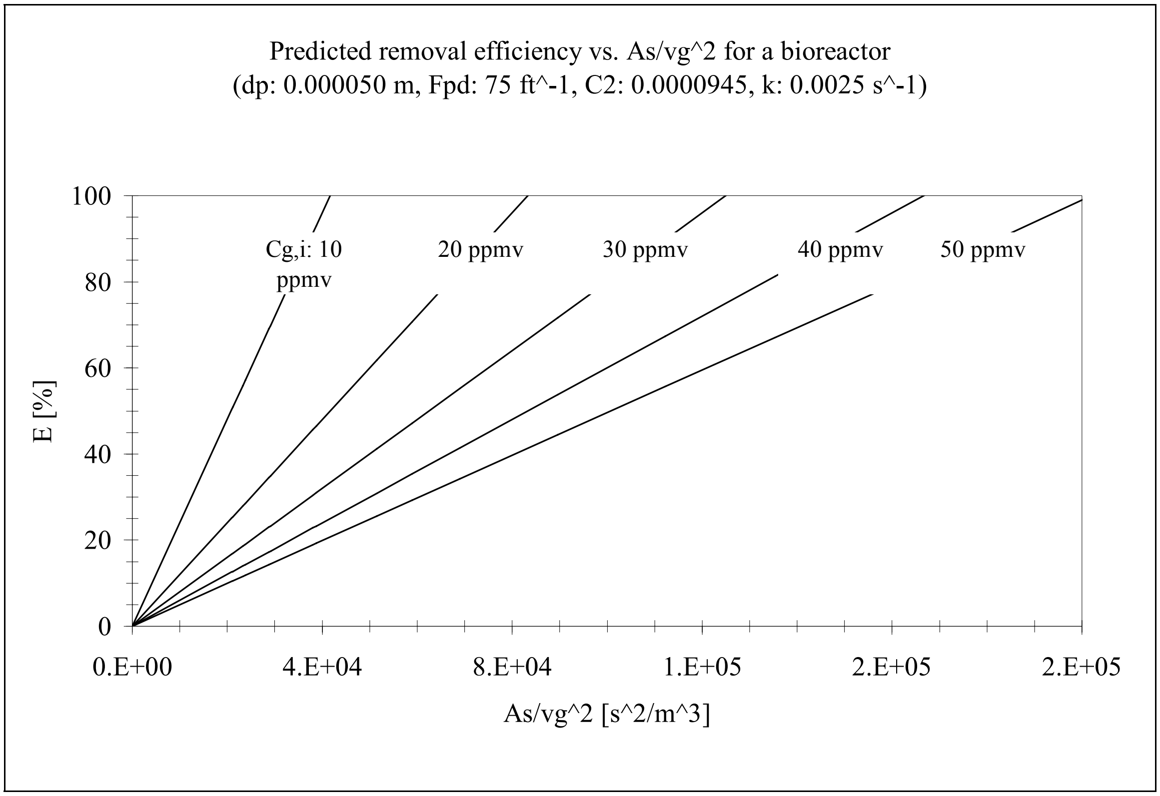

Figure 2. Removal efficiency E for H_2S as a function of $A_s v_g^{-2}$ for different inlet substrate concentrations $C_{g,i}$

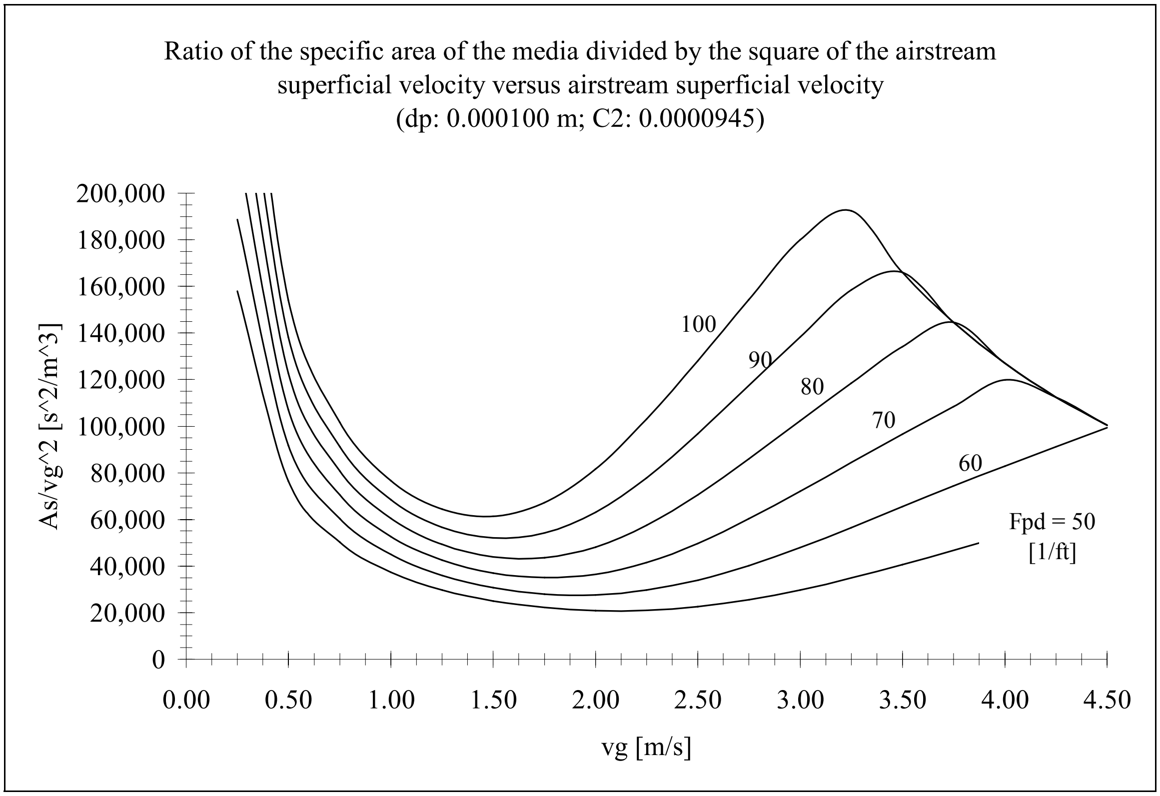

Figure 3. Effect of gas superficial velocities v_g on the function $A_s v_g^{-2}$ for close pore foam media.

Figure 4 is a direct graphical representation of the different removal efficiencies attained when increasing the superficial gas velocity for different H_2S inlet concentrations. The counteracting effect of the gas velocity is proven through the minima shown.

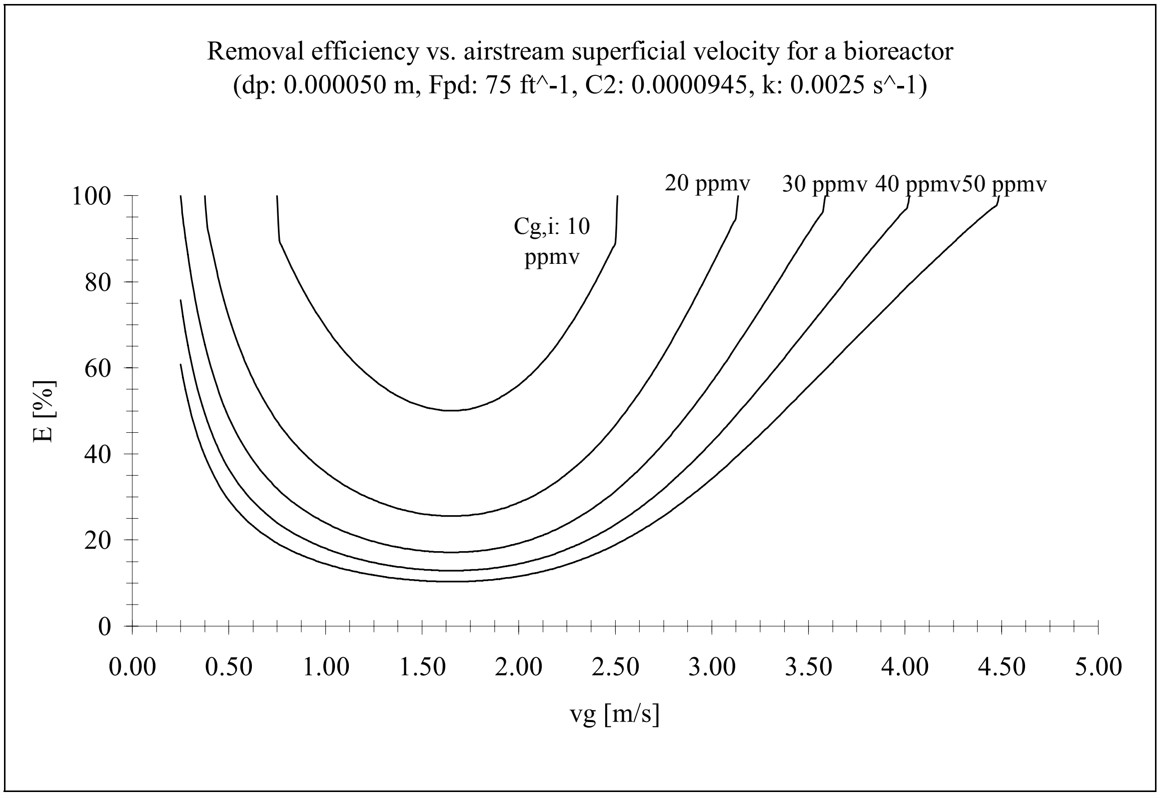

Figure 4. Effect of gas superficial velocities v_g on the H_2S removal efficiency E for a bioreactor.

Kinetic parameters for the H_2S and other SRC are shown in Tables 1 and 2. Values for H_2S were obtained by fitting data from a full scale case study presented by Gabriel and Deshusses (2003a,b). For Methyl Mercaptan (MT) and Dimethyl Mercaptan (DMS), values for the kinetic parameters were assumed to have the same ratio to H_2S as those reported by Hirai *et al*. (1990) and Cho *et al*. (1991) in their works carried out in peat biofilters with and without previous acclimatization with specific trends of bacteria. For Carbonyl Sulfide (CS_2), since no data was available, kinetic parameters were assumed to equivalent to those of Dimethyl Disulfide (DMDS) as reported by the previous authors, since both compounds have two carbon-sulfur double bonds. Gabriel and Deshusses (2003a,b) reported that for a bioscrubber that was converted to biofilter by inserting highly open porous polyurethane foam pieces (d_p: 2000 μm) H_2S removal efficiencies around 98% were attained at EBRT as low as 2 seconds (v_g: 1.8 m/s) for concentrations as high as 30 ppm_v.

Table 2. Values of transport and kinetic parameters for other SRC (Figures 5 and 6)

Parameter	MT	DMS	CS_2
k [s^{-1}]	0.00054	0.00023	0.00056

K_s [kg·m^{-3}]	$9\cdot10^{-8}$	$9\cdot10^{-8}$	$4\cdot10^{-8}$
D_f [m^{-2}·s^{-1}]	$1.18\cdot10^{-9}$	$1.08\cdot10^{-9}$	$0.80\cdot10^{-9}$
D_l [m^{-2}·s^{-1}]	$1.48\cdot10^{-9}$	$1.35\cdot10^{-9}$	$1.00\cdot10^{-9}$
H	0.205	0.085	0.743

The results shown in Figure 5 attempt to illustrate that the high values of the relationship $A_s v_g^{-2}$ can explain why such performance was observed. The calculated specific area of the foam media is higher than 100,000 m^{-1}, which results from almost 96% of the incoming gas stream flowing within the foam rather than around it. Although the original work refers to H_2S as substrate biodegraded in the case study, other pollutants such as MT, DMS and CS2 were also included in the simulation for the purpose of illustration at the same design conditions. Inlet concentrations of 5.0 ppm$_v$ (MT), and 1.0 ppm$_v$ (DMS and CS_2) were chosen since they are typical of most wastewater treatment plants.

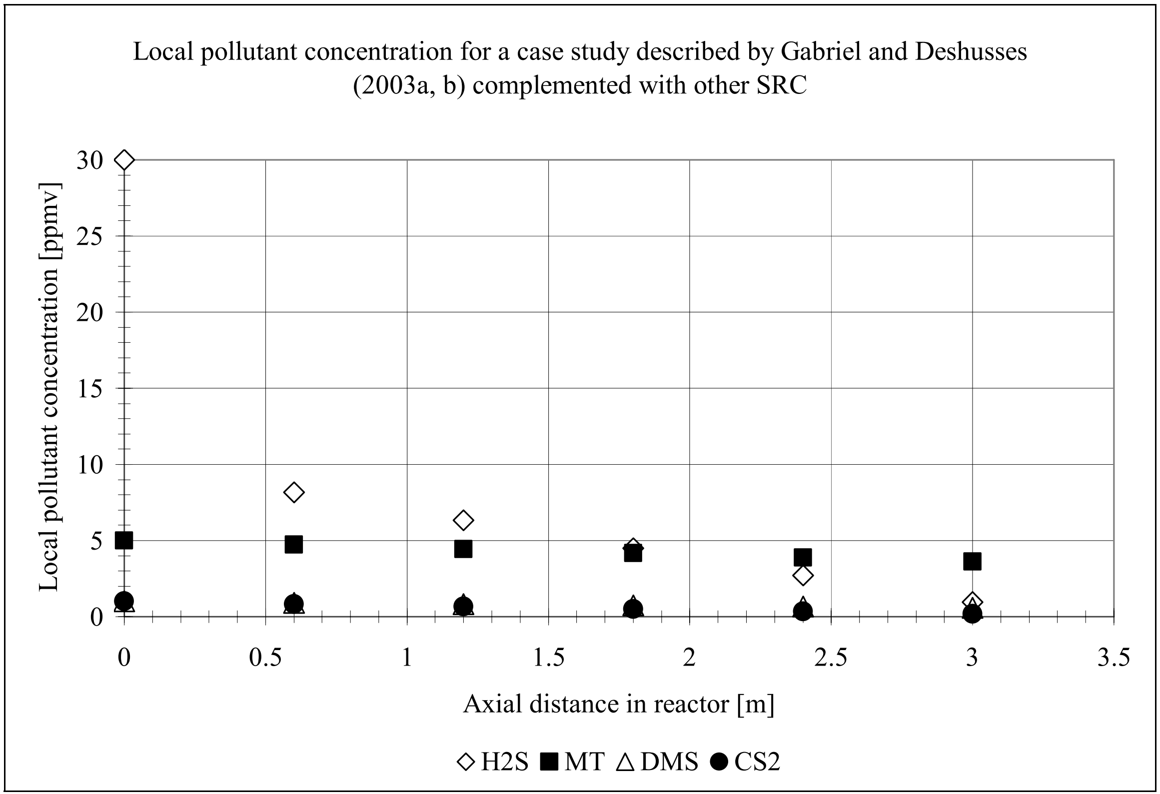

Figure 5. Pollutant concentration for different SRC treated under the conditions described on the case study reported by Gabriel and Deshausses (2003a,b)

In calculating the results presented in Figure 5, it was assumed that the biofilm thickness and density are solely function of the H_2S local concentrations and biokinetics, since it is this compound the one present in the highest concentration when entering the system and it is the easiest biodegradable. Different values of the local removal efficiency are shown in Figure 6 for all of the species. Here, the local removal efficiencies and substrate concentrations are shown for each section of the biofilter along its height. From this Figure, it is clear the removal efficiencies increase as we move upwards in the bioreactor, mainly due to a reduction in the concentration and a higher effective specific area. The overall removal efficiency calculated with the model is 90%, which at the simulated inlet concentration of 30 ppm_v is comparable to the removal efficiency reported by Gabriel and Deshusses (2003a,b) of 98% for H_2S concentrations lower than 30 ppm_v and 10 ppm_v in average. Though the maximum Monod's velocity of reaction k is lower for CS_2 than MT and DMS, its higher solubility promotes a better local removal efficiency, as shown in Figure 6.

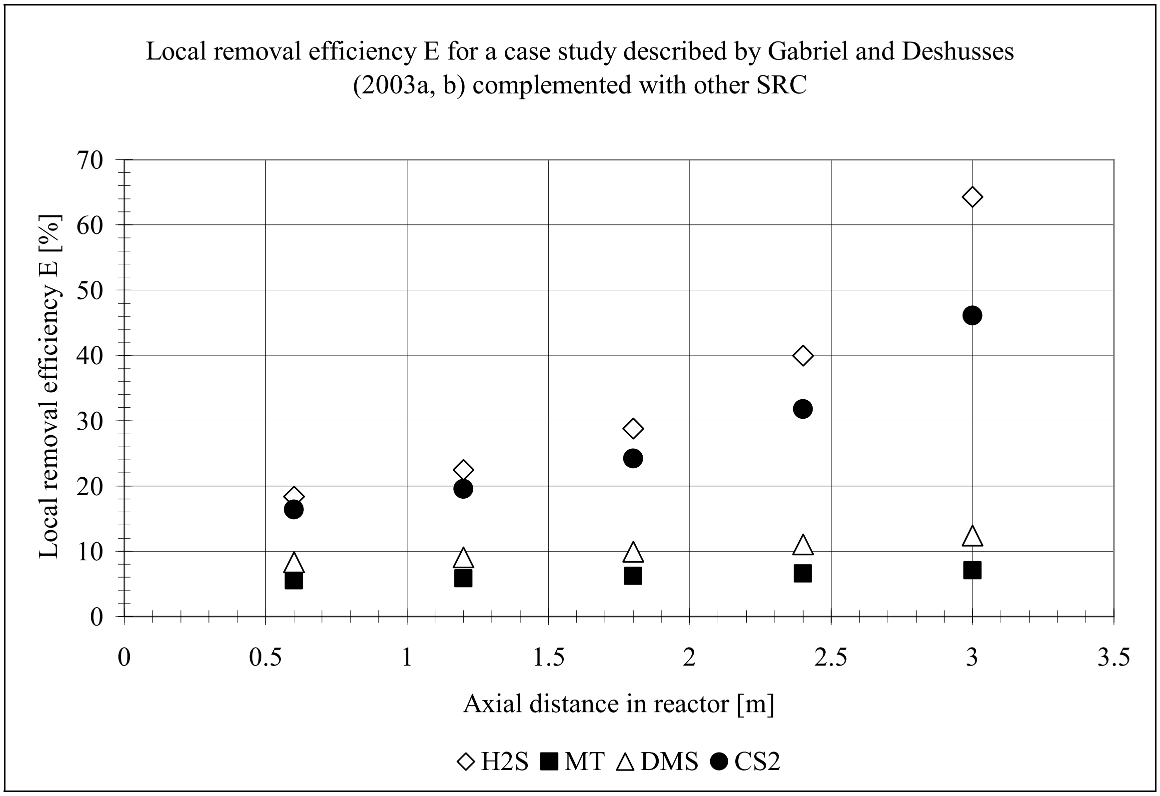

Figure 6. Local removal efficiencies E for different SRC treated under the conditions described on the case study reported by Gabriel and Deshausses (2003a,b)

4. Conclusions

Based on the amount of gas flowing within and past porous media, a model that allows for prediction of the performance of a bioreactor packed with foam pieces is proposed. The model predicts the impact of the media design (pore size, porosity, foam packing factor) on the gas flow distribution within the reactor and consequently the bioreactor performance. A case study reported elsewhere where H_2S is treated in a foam packed bioscrubber was successfully simulated using the model and its results complemented with other SRC treated at typical industrial conditions for comparison purposes.

5. List of symbols

A_s: Effective specific area [m^{-1}]
A_b: External foam specific area [m^{-1}]
A_f: Internal foam specific area [m^{-1}]
b: Decay coefficient (See Rittmann and McCarthy, 1980) [s^{-1}]
C_f: Substrate concentration in the biofilm [$kg \cdot m^{-3}$]
C_g: Substrate concentration in the gas [$kg \cdot m^{-3}$]
C_l: Substrate concentration in the liquid [$kg \cdot m^{-3}$]
C_2: Empirical coefficient for each type of packing material, See Robbins (1991) [1]
D_f: Effective diffusivity in biofilm [$m^2 \cdot s^{-1}$]
D_l: Substrate diffusivity in liquid [$m^2 \cdot s^{-1}$]
d_p: Pore size [m]
E: Removal Efficiency [1]
F_{pd}: Packing factor [ft^{-1}]
g: Gravity [$10\ m \cdot s^{-2}$]
H: Dimensionless Henry's law constant [1]
J_f: Diffusive flux in the biofilm [$kg \cdot m^{-2} \cdot s^{-1}$]
J_g: Diffusive flux in the gas [$kg \cdot m^{-2} \cdot s^{-1}$]
J_l: Diffusive flux in the liquid [$kg \cdot m^{-2} \cdot s^{-1}$]
k: Maximum Monod's velocity of reaction,bstrate [s^{-1}]
k_l: Substrate liquid phase mass transfer coefficient [$m \cdot s^{-1}$]
K_s: Half saturation constant, single substrate [$kg \cdot m^{-3}$]
l: Strut length [m]
L: Reactor length [m]
$\left.\frac{\Delta P}{L}\right|_f$: Gas stream pressure drop within the foam [$kg \cdot m^{-2} \cdot s^{-2}$]
$\left.\frac{\Delta P}{L}\right|_b$: Gas stream pressure drop in the bed [$kg \cdot m^{-2} \cdot s^{-2}$]
R_{C_f}: Biodegradation rate [$kg \cdot m^{-3} \cdot s^{-1}$]
t_s: Strut thickness [m]
v_f: Superficial gas velocity through foam packing [$m \cdot s^{-1}$]
v_g: Superficial gas velocity [$m \cdot s^{-1}$]
v_l: Superficial liquid velocity [$m \cdot s^{-1}$]
X_f: Biofilm density [$kg \cdot m^{-3}$]

x: Axis tag [m]
y: Axis tag [m]
Y: Yield coefficient [1]

Greeks

α: Factor Equation (16)
δ_f: Biofilm thickness [m]
δ_l: Liquid thickness [m]
ε_b: Foam porosity [1]
ε_f: Foam porosity [1]
μ_l: Liquid viscosity [$kg \cdot m^{-1} \cdot s^{-1}$]
ρ_l: Liquid density [$kg \cdot m^{-3}$]

Subscrpits

i: Inlet
o: Outlet, initial

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