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Modeling the heat effects in waste air trickling biofilters

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ABSTRACT

In this paper a mechanistic model was developed to predict the performance of a trickling biofilter as a function of temperature. Energy and mass balances were used to obtain the model equations. The expression for the bioreaction rate was modified in a way that it included the effect of temperature on the rate of bioreaction. The effects of temperature on Henry's law constant and diffusivity of the pollutant were also considered. The model equations were solved using finite volume method. The results in the literature from a bench scale trickling biofilter treating toluene were used to verify the model. The model predicted the experimental data reasonably well. Sensitivity analysis showed that the performance of a trickling biofilter is sensitive to the variations in maximum specific growth rate of microorganisms, and Henry's law constant of the pollutant as a result of variation in temperature. The model could also predict the water loss due to the evaporation of the liquid medium.

1. Introduction

Emission of volatile organic compounds (VOC_s) from industrial sites is a major environmental problem. The industrial sect in many countries is mandated to keep the emissions below regulatory levels. Various methods have been developed to reduce the amount of VOCs in airstreams. The methods are generally classified as physical (such as adsorption) chemical (such as incineration), and biological (such as biofiltration). Biological methods have been proved to be economical for the treatment of air streams with relatively low concentration of pollutants.

Biological air treatment systems are classified as biofilters, trickling biofilters, 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 biofilter is kept wet by humidification of the entering polluted air and/or intermittent irrigation of the bed. Trickling biofilters 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 trickling biofilters 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 which 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].

Several factors affect the performance of a (trickling) biofilter. The type and moisture of packing materials, pH, temperature, nutrient availability, and pollutant toxicity are some of the factors affecting the performance of (trickling) biofilters. A large body of the literature exists on the effect of most of the mentioned factors on the performance of (trickling) biofilters [2–5]. The effect of temperature, however, has not been investigated extensively. Campbell and Connor investigated the effect of temperature on the removal efficiency of an industrial scale biofilter treating solvent vapors from a printing press plant. Although the inlet air temperature fluctuated between 19 °C and 26 °C, no considerable change in removal efficiency was noticed. Campbell and Connor supposed that the rapid fluctuation in inlet air temperature did not affect the bed temperature [6]. Elmrini et al. monitored the elimination capacity of a bench scale biofilter treating xylene, as a function of the average bed temperatures (average value of temperature measurements in three levels along the height of the biofilter). The elimination capacity of the biofilter was about 10 g m^{-3} h^{-1} at the average bed temperature of 26 °C. The figure increased to about 60 g m^{-3} h^{-1} when the average bed temperature increased to 28 °C. They concluded that the elimination capacity of a biofilter was strongly affected by the bed temperature [7]. Lim et al. investigated the effect of inlet air temperature on the performance of a biofilter treating ethanol vapors. The inlet air temperature varied from 25 °C to 40 °C. The biofilter performed optimally when the inlet air temperature was 30 °C [8]. Elsgaard investigated the variation in performance of a biofilter when the temperature of the incubator in which the biofilter was under operation, varied

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Nomenclature

A	cross-section area of the trickling biofilter (m^2)
A_s	specific surface area of biofilm ($m^2\ m^{-3}$)
c	specific heat capacity of the trickling medium ($kJ\ kg^{-1}\ K^{-1}$)
c_s	specific heat capacity of humid air ($kJ\ kg^{-1}\ K^{-1}$)
cp_{air}	specific heat capacity of air ($kJ\ kg^{-1}\ K^{-1}$)
cp_v	specific heat capacity of vapor ($kJ\ kg^{-1}\ K^{-1}$)
C_b	pollutant concentration in biofilm ($g\ m^{-3}$)
$C_{b,i,j}$	pollutant concentration at the node j in biofilm corresponding to the node i along the height of the trickling biofilter ($g\ m^{-3}$)
C_g	pollutant concentration in gas phase ($g\ m^{-3}$)
C_{gin}	pollutant concentration in gas phase at the inlet of each segment ($g\ m^{-3}$)
C_{ginlet}	pollutant concentration in gas phase at the inlet of the trickling biofilter ($g\ m^{-3}$)
C_{gout}	pollutant concentration in gas phase at the outlet of each segment ($g\ m^{-3}$)
$C_{g,i}$	pollutant concentration in gas phase at the node i ($g\ m^{-3}$)
C_l	pollutant concentration in liquid phase ($g\ m^{-3}$)
C_{lin}	pollutant concentration in liquid phase at the inlet of each segment ($g\ m^{-3}$)
C_{linlet}	pollutant concentration in liquid phase at the inlet of the trickling biofilter ($g\ m^{-3}$)
C_{lout}	pollutant concentration in liquid phase at the outlet of each segment ($g\ m^{-3}$)
$C_{l,i}$	pollutant concentration in liquid phase at the node i ($g\ m^{-3}$)
D_T	diffusion coefficient of pollutant in biofilm as a function of temperature ($m^2\ s^{-1}$)
D_{298}	diffusion coefficient of pollutant in biofilm at 298 K ($m^2\ s^{-1}$)
$D_{T,i}$	diffusion coefficient of pollutant in biofilm at T_i ($m^2\ s^{-1}$)
H	humidity of air (kg vapor/kg air)
H_T	Henry's law constant for the distribution of the pollutant between the air and liquid at temperature T (dimensionless)
$H_{T,i}$	Henry's law constant for the distribution of the pollutant between the air and liquid at temperature T_i (dimensionless)
h	enthalpy of humid air ($kJ\ kg^{-1}$)
h_{in}	enthalpy of humid air at the inlet of each segment ($kJ\ kg^{-1}$)
h_{inlet}	enthalpy of humid air at the inlet of the trickling biofilter ($kJ\ kg^{-1}$)
h_{out}	enthalpy of humid air at the outlet of each segment ($kJ\ kg^{-1}$)
h_i	enthalpy of humid air at the node i ($kJ\ kg^{-1}$)
K_I	inhibition constant in the expression for the bioreaction rate ($g\ m^{-3}$)
k_s	half saturation constant in the expression for the bioreaction rate ($g\ m^{-3}$)
K_{La}	volumetric mass transfer coefficient between air and the liquid (s^{-1})
L	biofilter height (m)
M_{air}	molar weight of air
M_v	molar weight of water
m	distribution constant of the pollutant in liquid/biofilm system (dimensionless)
P_t	atmospheric pressure (Pa)
P_v^*	vapor pressure of water (Pa)
Q	the amount of heat released per gram of toluene degraded ($kJ\ g^{-1}$)
Q_g	gas flow rate ($m^3\ s^{-1}$)
Q_l	liquid flow rate ($m^3\ s^{-1}$)
$r(C_b,T)$	bioreaction rate as a function pollutant concentration and temperature in biofilm ($g\ m^{-3}\ s^{-1}$)
u_g	superficial velocity of gas in the trickling biofilter ($m\ s^{-1}$)
u_l	superficial velocity of liquid in the trickling biofilter ($m\ s^{-1}$)
T	Temperature of the gas, liquid, and biofilm along the height of biofilter (K)
T_{inlet}	Temperature of the gas and liquid at the inlet of the trickling biofilter (K)
T_{outlet}	Temperature of the gas and liquid at the outlet of the trickling biofilter (K)
To	optimum temperature for microbes (K)
x	position in biofilm depth (m)
X_v	biofilm density ($g\ m^{-3}$)
z	position along the height of the trickling biofilter (m)
$Y_{X/Y}$	biomass growth yield on toluene (g biomass/g toluene)
μ_{maxo}	maximum specific growth rate of microorganisms in biofilm at To (s^{-1})
$\mu_{max}(T)$	maximum specific growth rate of microorganisms in biofilm as a function of temperature (s^{-1})
δ	biofilm depth (m)
ρ_l	density of liquid ($kg\ m^{-3}$)
ρ_g	density of air ($kg\ m^{-3}$)
λ_0	enthalpy of vaporization of water at a reference temperature ($kJ\ kg^{-1}$)

from 21 °C to 10 °C. The biofilter was treating an ethylene contaminated air. The inlet concentration of ethylene was 117 ppm and the outlet concentration was below 1 ppm when the temperature was 21 °C. When the biofilter was placed in an incubator with the temperature of 10 °C the outlet concentration increased to 46 ppm, but after 2 days it started to decrease and after 18 days the outlet concentration was essentially the same as it was under 21 °C [9].

The bacteria responsible for the degradation of pollutants in biofilters are mostly mesophiles. Mesophilic bacteria are active in the temperature range of 15–40 °C with the optimum temperature of around 35 °C [10]. The temperature of the packing materials in a (trickling) biofilter is mainly affected by the temperature of the inlet air (and liquid medium) and the biological activity of microorganisms. Biofilters may perform better under suboptimal temperatures for microbes because of the effect of temperature on Henry's law constant of pollutants. Increasing the temperature of packing materials toward optimal temperature for microbes, causes also increase in Henry's law constant of pollutants. Increase in Henry's law constant means decrease in pollutant absorption on packing materials. Deshusses and Johnson examined the elimination capacity of a biofilter for various biodegradable organic compounds, and concluded that Henry's law constant plays an important role in the elimination capacity of biofilters [11]. The effect of temperature on the diffusivity of pollutants and oxygen could also potentially affect the elimination capacity of (trickling) biofilters.

Increase or decrease in temperature of a biological waste air treatment system may cause the development of a new microbial consortium better suited to the new temperature. The negative impacts of temperature change, then, may be compensated by bet-

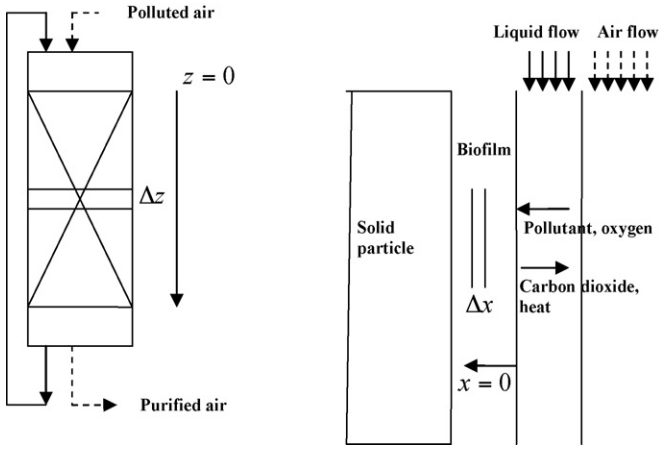

Fig. 1. Schematic of a cocurrent trickling biofilter and the mechanism occurs at the surface of particles.

ter activity of the new consortium. Cox et al. showed this fact using two identical trickling biofilters, one of them working at 22 °C and the other at 53 °C. The trickling biofilters were treating ethanol. The elimination capacities of both systems were almost equal despite the large difference in temperatures. Microbiological tests showed that the microbial consortia in the systems were not the same despite using the same source for initial inoculation. The high temperature trickling biofilter contained a group of thermophilic or thermotolerant microorganisms [12]. Developing a new consortium, however, may take several weeks, and variation in performance of a (trickling) biofilter due to the temperature change in short terms might not be attributed to change in microbial community.

In this paper, a mechanistic model is developed under the assumption of non-isothermal conditions to predict the effect of temperature variations on the performance of a trickling biofilter. Toluene is considered as a model pollutant.

2. Theory

2.1. Model development

Fig. 1 shows a schematic of a trickling biofilter, and the process occurs on the packing materials. Following assumptions were used to derive the governing equations for a cocurrent trickling biofilter:

1- The ideal gas law applies for the gas phase.
2- The gas and liquid flows through the bed of the trickling biofilter are ideal plug flows and the variations of concentration and temperature along the diameter are neglected.
3- Biodegradation of the pollutant occurs only in biofilm.
4- Oxygen is not limited for the process.
5- There is no net biomass accumulation in the bed of the trickling biofilter.
6- The rate of biodegradation depends on the concentration of the pollutant in biofilm and is expressed by an Andrew type rate equation [13]. To consider the effect of temperature on the rate of biodegradation the Andrew type relation is modified as below:

$$r(C_b, T) = \frac{\mu_{\max}(T) X_v}{Y_{X/Y}} \frac{C_b}{k_s + C_b + (C_b^2/K_I)} \quad (1)$$

where:

$$\mu_{\max}(T) = \mu_{\max o} \exp\left[\frac{-(T - To)^2}{175}\right] \quad (2)$$

The term $\exp[-(T-To)^2/175]$ ensures the optimum effect of temperature on the bioreaction rate at *To*, and a decreasing trend as the temperature deviates from this point. Number 175 is a fit parameter.

7- The mechanism of mass transfer in biofilm is diffusion.
8- The effective diffusivity of the pollutant in biofilm is the diffusivity in water corrected by the correlation of Fan et al. [14].
9- The process is under steady state conditions and the diffusion of pollutant occurs only through specific surface area of biofilm (surface area of biofilm per unit volume of biofilter bed).
10- The pollutant concentration at the liquid/biofilm interface is always in equilibrium with the bulk liquid concentration. These are related by a constant distribution coefficient.
11- The thickness of biofilm is constant all over the biofilter. 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.
12- There is no temperature gradient in biofilm. Heat is transferred from the biofilm (where it is produced by bioreaction) to the liquid and gas phases. Due to the small thickness of biofilm it is reasonable to neglect temperature gradient in biofilm. The temperature of biofilm in each position along the height of the biofilter is equal to the temperature of the liquid and gas phases at the same position.
13- The air is saturated with water vapor throughout the trickling biofilter. Although the temperature rises due to the bioreaction in the biofilm, the air remains saturated due to the water evaporation.
14- The heat transfer between the wall of the trickling biofilter and the surrounding atmosphere is negligible.
15- For each gram of the pollutant which is degraded, a specific amount of heat is released. The effect of temperature on this parameter is neglected.
16- The rate of the pollutant mass transfer from the gas to the liquid is approximated by a linear driving force model.

A differential element is considered along the height of the trickling biofilter. The process involves three phases: gas phase, liquid phase and biofilm. To model the process mass and energy balance equations are written for each phase (the energy balance is not needed for the biofilm due to the assumptions (12)).

$$u_g \frac{dC_g}{dz} + K_{La}\left(\frac{C_g}{H_T} - C_l\right) = 0 \quad (3)$$

$$C_g(0) = C_{ginlet} \quad (4)$$

a—mass balance for the pollutant in the gas phase [15]:

$$H_T = \exp\left(10.79 - \frac{3600}{T}\right) \quad (5)$$

$$u_l \frac{dC_l}{dz} - K_{La}\left(\frac{C_g}{H_T} - C_l\right) - D_T A_s \frac{dC_b}{dx}|_{x=0} = 0 \quad (6)$$

$$C_l(0) = C_l(L) \quad (7)$$

b—mass balance for the pollutant in the liquid phase [16]:

$$D_T = \frac{TD_{298}}{298} \quad (8)$$

c—energy balance:

$$-D_T A_s Q \frac{dC_b}{dx}|_{x=0} = \rho_l c_l u_l \frac{dT}{dz} + \rho_g u_g \frac{dh}{dz} \quad (9)$$

$$T(0) = T_{inlet} \quad (10)$$

$$h(0) = h_{inlet} \quad (11)$$

where

$$h(z) = c_s(z)T(z) + \lambda_0 H(z), \quad (12)$$

Table 1
Model parameters.

Parameter	Units	Value	Reference
L	m	0.5	[17]
A	m^2	0.07	[17]
D_{298}	$m^2\ s^{-1}$	8.5×10^{-10}	[17]
Q	$KJ\ g^{-1}$	30.45	[17]
X_v	$g\ m^{-3}$	100,000	[17]
$Y_{X/Y}$	g biomass/g toluene	0.708	[17]
k_s	$g\ m^{-3}$	11.03	[17]
k_l	$g\ m^{-3}$	78.94	[17]
δ	m	35×10^{-6}	The average of the values used in [17]
c	$kJ\ kg^{-1}\ K^{-1}$	4.2	[16]
To	K	308	[10]
m	–	1	Explained in the text
μ_{maxo}	s^{-1}	4.2×10^{-4}	[17]

$$c_s(z) = c_{pair} + c_{pv}H(z), \tag{13}$$

$$c_{pair} = 0.962 + 1.648 \times 10^{-3}\ T - \frac{458.7}{T^2}, \tag{14}$$

$$c_{pv} = 1.602 + 6.697 \times 10^{-4}\ T + \frac{5588.85}{T^2} \tag{15}$$

$$H(z) = \frac{M_v P_v^*}{M_{air}(P_t - P_v^*)}, \tag{16}$$

$$P_v^* = 133.29 \exp\left[18.30 - \frac{3816.44}{-46.13 + T(z)}\right] \tag{17}$$

Eq. (9) indicates that under steady state conditions, the heat released by bioreaction causes an increase in enthalpy of the liquid (the first term in the right hand of the equation) and humid enthalpy of the air (the second term in the right hand of the equation).

d—mass balance for the pollutant in biofilm:

$$D_T \frac{d^2 C_b}{dx^2} - r(C_b, T) = 0 \tag{18}$$

$$C_b(0, z) = \frac{C_l(z)}{m} \tag{19}$$

$$\frac{dC_b(\delta, z)}{dx} = 0 \tag{20}$$

The distribution constant for toluene in water/biofilm system is considered to be unity due to the high water content of the biofilm.

2.2. Solution of the model equations

The model equations were discretized using the finite volume method. The resulting algebraic equations were solved using Jacobi iteration method. The method of solution has been presented in appendix A.

3. Results and discussions

The model was used to describe the performance of a trickling biofilter which was used to remove toluene from air by Liao et al. [17]. The biokinetic and operational parameters have been summarized in Table 1. K_{La} and the specific surface area for biofilm (A_s) were estimated from the correlations in the literature [18,19].

3.1. Comparison between model predictions and experimental data

Fig. 2 shows the removal efficiency of the trickling biofilter as a function of the temperature of the trickling medium. The removal efficiency increases with temperature, and decreases after passing from an optimum range. The results indicate that although the trickling biofilter is active under temperatures as low as 283 K, and as high as 333 K, it performs optimally under the temperature range of 303–313 K. While the model predicts the removal efficiency in the optimum range reasonably well, below and above the range over prediction and under prediction are observed, respectively. These deviations can be attributed to the simplifying assumption that the gas and liquid enter the system at the same temperature. The model calculates Henry's law constant as a function of the liquid temperature with the assumption of thermal equilibrium between gas and liquid at each position along the height. In practice, however, for each experiment only the inlet liquid temperature was kept constant using a heat exchanger. So the temperature at the gas/liquid interface may differ from the temperature of the liquid bulk. As it will be demonstrated later, Henry's law constant considerably affects the performance of a trickling biofilter. Assuming the inlet gas temperature of 298 K for the experiments, the real Henry's law constant would be higher than the calculated one for the liquid temperatures below 298 K (the reason for over prediction) while it would be lower for the liquid temperatures above 298 K (the reason for under prediction). Therefore this model is well suited for the cases where the liquid and the gas temperatures are close to each other.

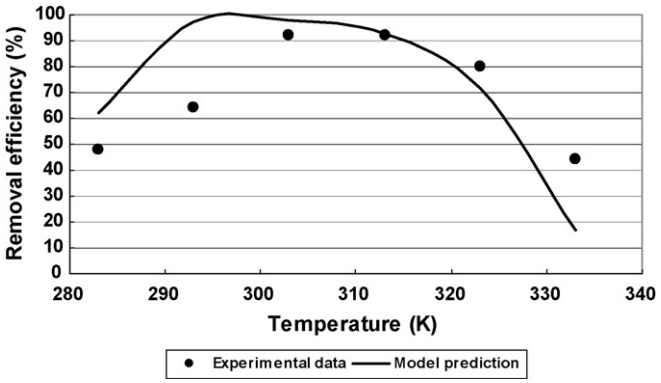

Fig. 2. Performance of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) as a function of the temperature of the liquid medium. $C_{ginlet} = 1.2\ g\ m^{-3}$, $u_g = 11.32\ m\ h^{-1}$, $u_l = 0.23\ m\ h^{-1}$.

In addition to adopting a different approach, the present model incorporates a term in the expression for the bioreaction rate which enables it to predict the increasing decreasing trend in performance as a function of temperature. The model which was presented by Liao et al. is unable to simulate this trend because it does not consider the effect of temperature on the bioreaction rate [17].

The temperature of the trickling medium varies along the height of the trickling biofilter since biological reactions are exothermic. Fig. 3 shows the difference between the inlet and outlet temper-

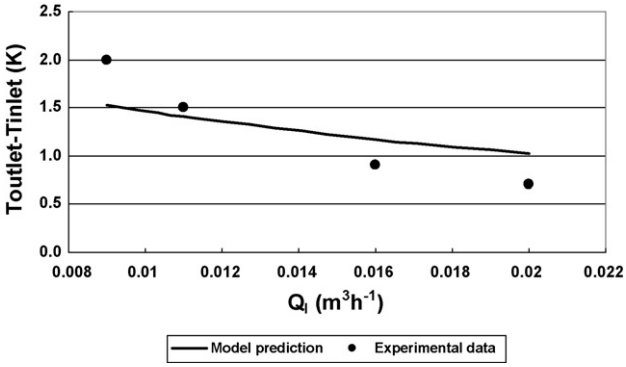

Fig. 3. The difference between the inlet and outlet temperature of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) as a function of the liquid flow rate. $C_{ginlet} = 2.5\ g\ m^{-3}$, $u_g = 22.65\ m\ h^{-1}$.

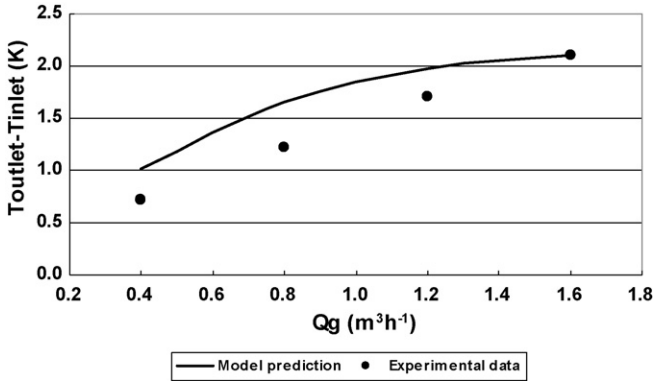

Fig. 4. The difference between the inlet and outlet temperature of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) as a function of the gas flow rate. $C_{ginlet} = 3.5\ g\ m^{-3}$, $u_l = 0.13\ m\ h^{-1}$.

atures as a function of liquid flow rate. The difference becomes smaller as the liquid flow rate increases. Fig. 4 shows the difference between the inlet and outlet temperatures of the trickling biofilter as a function of the air flow rate. With the increase in the air flow rate at constant inlet concentration the difference between the inlet and outlet temperatures becomes larger. Fig. 5 shows the difference between the inlet and outlet temperatures of the trickling biofilter as a function of the inlet pollutant concentration. With the increase in inlet concentration at constant air and liquid flow rates, the difference between the inlet and outlet temperature becomes larger. In all the cases the model predicts the experimental data reasonably well.

3.2. Sensitivity analysis

The maximum specific growth rate of microorganisms, Henry's law constant of the pollutant, and the diffusivity of the pollutant in biofilm are temperature dependent parameters. In this part a sensitivity analysis is performed to find out the relative importance of the parameters on the performance of a trickling biofilter. To perform the sensitivity analysis for each parameter, all other parameters were calculated at 298 K, and the value of the parameter varied as a function of temperature in the range of 283–333 K.

Fig. 6 shows the performance of the trickling biofilter as a function of Henry's law constant. As the temperature increases Henry's law constant also increases, and the removal efficiency decreases. The reduction in removal efficiency is due to lower solubility of the pollutant in biofilm. Fig. 7 shows the performance of the trickling biofilter as a function of the diffusivity of the pollutant in biofilm.

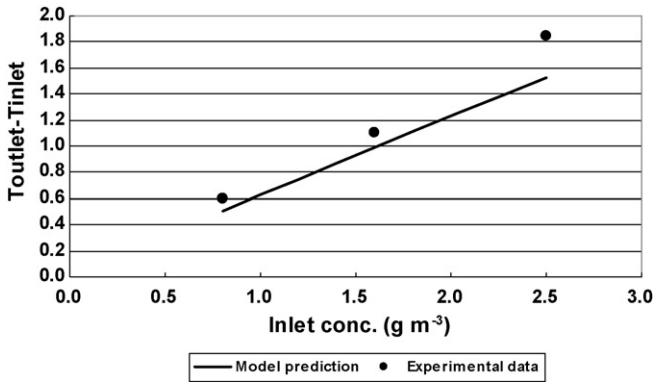

Fig. 5. The difference between the inlet and outlet temperature of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) as a function of the inlet gas concentration. $u_g = 22.65\ m\ h^{-1}$, $u_l = 0.13\ m\ h^{-1}$.

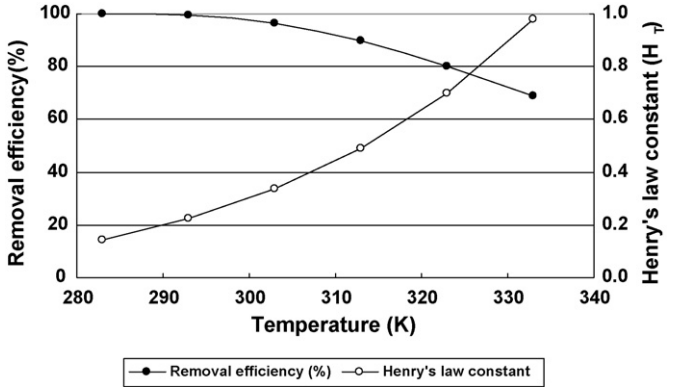

Fig. 6. The sensitivity of the performance of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) to Henry's law constant. $C_{ginlet} = 1.2\ g\ m^{-3}$, $u_g = 11.32\ m\ h^{-1}$, $u_l = 0.23\ m\ h^{-1}$.

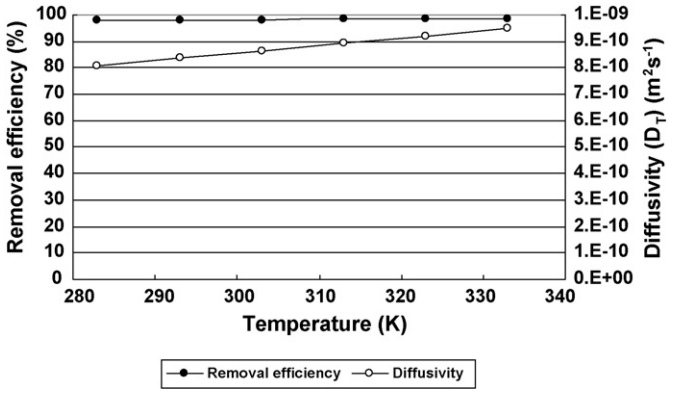

Fig. 7. The sensitivity of the performance of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) to the diffusivity of the pollutant in biofilm. $C_{ginlet} = 1.2\ g\ m^{-3}$, $u_g = 11.32\ m\ h^{-1}$, $u_l = 0.23\ m\ h^{-1}$.

Although the diffusivity increases with the temperature, the performance of the trickling biofilter is not sensitive to this parameter in the temperature range which was tested. Fig. 8 shows the performance of the trickling biofilter as a function of the maximum specific growth rate of the microorganisms. The figure shows that the performance of a trickling biofilter is strongly dependent on the maximum specific growth rate. Overall, the results of the sensitivity analysis shows that the dependence of the maximum specific growth rate and Henry's law constant on temperature is important to be considered in design and analysis of trickling biofilters.

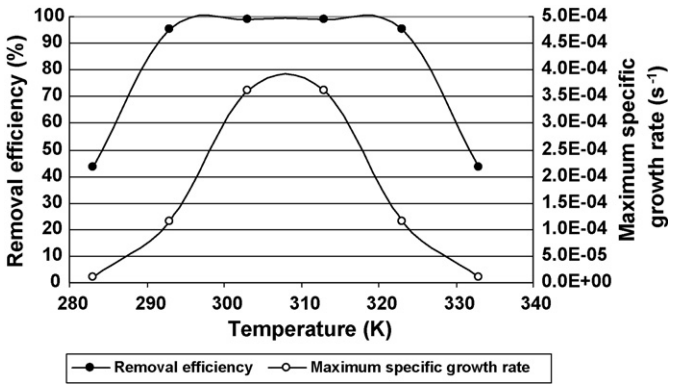

Fig. 8. The sensitivity of the performance of the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) to the maximum specific growth rate. $C_{ginlet} = 1.2\ g\ m^{-3}$, $u_g = 11.32\ m\ h^{-1}$, $u_l = 0.23\ m\ h^{-1}$.

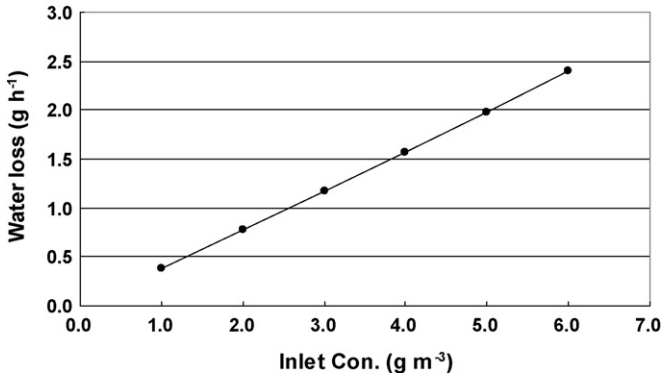

Fig. 9. Water loss due to the evaporation in the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) as a function of the pollutant concentration at the inlet. $u_g = 11.32\ m\ h^{-1}$, $u_l = 0.23\ m\ h^{-1}$.

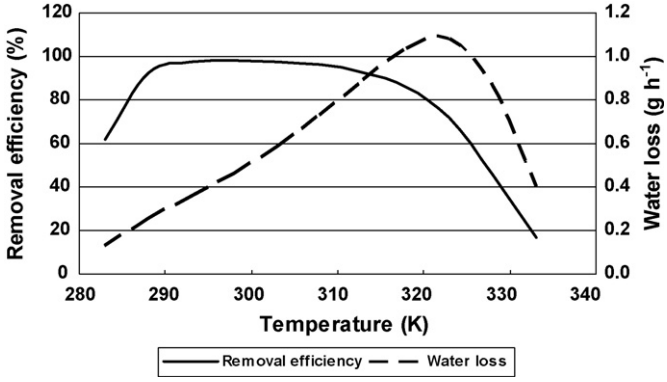

Fig. 10. Water loss due to the evaporation in the trickling biofilter ($A = 0.07\ m^2$, $L = 0.5\ m$) as a function of the temperature at the inlet. $C_{ginlet} = 1.2\ g\ m^{-3}$, $u_g = 11.32\ m\ h^{-1}$, $u_l = 0.23\ m\ h^{-1}$.

The model confirms that the difference between the inlet and outlet temperature of trickling biofilters is rather small. Ignoring this difference may not introduce a significant error in the design of trickling biofilters. But when different inlet temperatures are applied, the performance may vary considerably. This variation can be estimated using the present non-isothermal model.

3.3. Using the model to estimate water loss due to the evaporation

One of the advantages of the present model is the ability to estimate water loss in trickling biofilters due to evaporation. Note that the model assumes that the air is saturated throughout the trickling biofilter. The assumption is reasonable because of the efficient contact between air and liquid phases in the system. Having the air temperature at the inlet and outlet of a trickling biofilter, the humidity is calculated. Outlet humidity minus inlet humidity multiplied by air mass flow rate gives the rate of evaporation. Water evaporation is inevitable in trickling biofilters even if the inlet air is saturated. The humidity of the saturated air increases as a function of temperature. Fig. 9 simulates water loss as a function of inlet concentration. With the increase in inlet concentration, water loss increases. Fig. 10 shows water loss as a function of inlet temperature. Below the optimum range, as the temperature increases the removal efficiency and water loss also increase. Beyond the optimum range, as the removal efficiency decreases water loss also decreases. Maximum rate of water loss, however, does not correspond to the maximum removal efficiency. This is because of the faster change in saturation humidity of air as a function of temperature at higher temperatures. Note that the results in this section were obtained with the assumption of inlet air saturation, so the water loss calculated is due to the temperature increase in the system.

4. Conclusion

A mechanistic model based on energy and mass balances was developed to predict the performance of a trickling biofilter as a function of temperature. The model predicted the performance of a bench scale trickling biofilter successfully. The model showed that the removal efficiency of a trickling biofilter increased with the increase in temperature and after reaching an optimum range it started to decrease. The model could also predict the temperature variation along the height of the tricking biofilter. Under the tested conditions in this work the temperature of the trickling medium increased up to about 2 K. The sensitivity analysis showed that the performance of a trickling biofilter was strongly sensitive to variation in the maximum specific growth rate, and Henry's law constant as a result of the variation in temperature. The model presented here can also predict water evaporation due to the increase in temperature in a trickling biofilter. This model can be a useful aid in design and analysis of trickling biofilters.

The important limitation of the present model is considering equal temperatures for gas, liquid, and biofilm. In practice, the temperature of gas and liquid may differ considerably. Improving the model by introducing heat transfer coefficient between the gas and liquid is among our future work in this area. The other limitation is that the model assumes air saturation from the inlet to the outlet of the system. If this assumption is not true, temperature variations and water loss calculated by the model would be considerably different from the experimental results.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.cej.2010.08.043.

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