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Modelling mass transfer properties in a biotrickling filter for the removal of isopropanol

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HIGHLIGHTS

- Dimensionless Henry's law constant of isopropanol rises by a factor of 1.8 per 10 °C.
- Mass transfer of isopropanol is highly influenced by temperature.
- Isopropanol mass transfer coefficient increases with gas velocity.
- Oxygen mass transfer coefficient depends on packing material and liquid velocity.
- Power law correlations appear suitable to model both mass transfer coefficients.

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ABSTRACT

A study was carried out to model mass transfer properties in biotrickling filters, treating isopropanol as the target pollutant. This study was extended to the mass transfer of oxygen related to the fact that the treatment of hydrophilic compounds by biotrickling filtration is often limited by oxygen. A simple method for each compound was developed based on their physical properties. The influence of temperature on Henry's law constant of isopropanol was determined. An increase of 1.8 per 10 °C for the dimensionless Henry's law constant was obtained. The determination of the overall mass transfer coefficients of isopropanol (K_Ga) was carried out, obtaining values between 500 and 1800 h^{-1} for gas velocities of 100 and 300 m h^{-1}. No significant influences were observed for either the liquid velocity or packing material. Also, the determination of overall mass transfer coefficients of oxygen (K_La) were carried out, obtaining values between 20 and 200 h^{-1} depending on the packing material for liquid velocities between 2 and 33 m h^{-1}. Structured packing materials exhibited greater mass transfer coefficients, while for random packing materials, the mass transfer coefficients clearly benefited from the high specific surface area. Mathematical correlations found in the literature were compared with the empirical data, showing that neither was capable of reproducing the mass transfer coefficients obtained empirically. Thus, empirical relationships between the mass transfer coefficients and the gas and liquid velocities are proposed to characterise the system.

1. Introduction

In recent decades, there has been an emergent interest in research into biotreatment as an alternative for the treatment of volatile organic compounds (VOC), which includes the biotrickling filter as one of the most applicable technologies (Devinny et al., 1999). The use of biotrickling filtration for the treatment of VOC it is frequent and has been shown to be capable of achieving high removal efficiencies. Considering that biotrickling filtration involves a series of complex physical, chemical and biological processes, further work is needed to determine the mechanisms that contribute to the observed behaviour (Iranpour et al., 2005). The most representative mechanisms in a biotrickling filter are mass transfer, diffusion and biological degradation. Typically, the process may be limited by mass transfer as well as kinetics. Unfortunately, research has been mainly focused on biodegradation kinetics rather than mass transfer (Dorado et al., 2009; Lebrero et al., 2012) and, despite being a key step in the process, the optimisation of mass transfer between the gas and the liquid/biofilm remains one of the most difficult aims to achieve. Relating to this, several authors (Dorado et al., 2009; Kim and Deshusses, 2008a) have emphasised the need to determine the mass transfer coefficients in order to develop simulations for the design and optimisation of biotrickling filters. Also, determining the mass

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transfer coefficient would facilitate the selection of the packing material and the modelling of bioreactors used for air pollution control.

As pointed by other authors (Dorado et al., 2009; Kim and Deshusses, 2008a; Pérez et al., 2006), the hydrodynamic conditions used in biofiltration are markedly different than those used in absorption processes, so the typical correlations used in these systems are not useful for predicting the phenomena occurring in biotrickling filters. Dorado et al. (2009) confirmed that using experimental global mass transfer coefficients appears to be the most suitable way to represent mass transfer in biotrickling filter systems; they pointed out the need for using the target pollutant for the determination of mass transfer coefficients.

Isopropanol is a hydrophilic compound typified by its high volatility and relatively low hazardous properties in comparison with other solvents. As a result, it is one of the most commonly used solvents in chemical industries as coating, printing, cleaning, among others, resulting in a large amount of emissions to the atmosphere that should be treated. Due to its low Henry's law constant in comparison with Henry's law constant of oxygen, its treatment by biofiltration implies that the process could be typically limited by the low concentration of oxygen in the biofilm. This could imply that that the penetration depth of oxygen in water or the biofilm is lower than that of the pollutant, causing anaerobic zones in the deeper parts of the biofilm close to the substratum (Shareefdeen and Singh, 2005). Experiments based on the physical properties of the gas and liquid phases have shown that the volumetric mass transfer coefficient could be influenced by the liquid phase at a similar level of contribution than the influence of the gas (Pérez et al., 2006). So, both influences should be assessed in order to characterise and improve the process.

The purpose of this research was to determine the mass transfer coefficients for the treatment of hydrophilic compounds using isopropanol and oxygen as reference components for various packing materials. To carry out this purpose, the following objectives were developed: (1) to establish a simple method to determine the mass transfer coefficients of typical hydrophilic compounds using isopropanol as the target pollutant, (2) to establish a simple method to determine the mass transfer coefficients of oxygen, (3) to determine the influence of gas and liquid velocities on the mass transfer coefficients and (4) to establish a mathematical relationship between the mass transfer coefficients and the operational conditions.

2. Materials and methods

2.1. Theory

The overall mass transfer coefficient expressed in the liquid phase is defined as a function of the individual mass transfer coefficients, and is related to the overall mass transfer coefficient expressed in the gas phase

$$\frac{1}{K_L a} = \frac{1}{HK_G a} = \frac{1}{k_L a} + \frac{1}{Hk_G a} \quad (1)$$

Depending on Henry's law constant of the substance, the main resistance to the transfer could be controlled only by one of these phases. Liss and Slater (1974) established that for Henry's law constants over 250 atm (mole fraction)$^{-1}$, the main resistance is controlled by the liquid film, while for Henry's law constants between 1 and 250 atm (mole fraction)$^{-1}$, the main resistance is a mix between the two phases, and for Henry's law constants up to 1 atm (mole fraction)$^{-1}$, the resistance is controlled by the gas film. Due to the existing differences between Henry's law constant of isopropanol (0.460 ± 0.124 atm (mole fraction)$^{-1}$ (Sander, 2005)) and oxygen (43922 ± 1679 atm (mole fraction)$^{-1}$), two different methods were developed to measure the mass transfer coefficients for each compound.

2.2. Determination of the mass transfer coefficient of isopropanol

2.2.1. Experimental set-up

As shown in Fig. 1, the system consisted of a column of methacrylate (14.4 cm internal diameter, 120 cm height) and a recirculation tank (5 L water volume). Two packing materials, one random (Flexiring 25 mm) and one structured (PAS Winded Media), were investigated; the characteristics of these materials are shown in Table 1. The packing height was 100 cm. The air stream (compressed, filtered and dried) was introduced through the bottom of the column, with the flow rate adjusted using a mass flow controller (Bronkhorst Hi-Tec, The Netherlands). The experiments were carried out at three superficial air velocities around 100, 150 and 300 m h^{-1} and the trickling water was recirculated using a centrifugal pump (HPR10/15, ITT, Great Britain) in counter-current mode with respect to the air flow rate, with a superficial water velocity of 2, 4, 7 and 13 m h^{-1}. The operational conditions were selected in order to evaluate the wide range used in biotrickling filters. The experiments were carried out at room temperature (21.5 ± 1.3 °C). For isopropanol, these changes in temperature imply variations in Henry's law constants

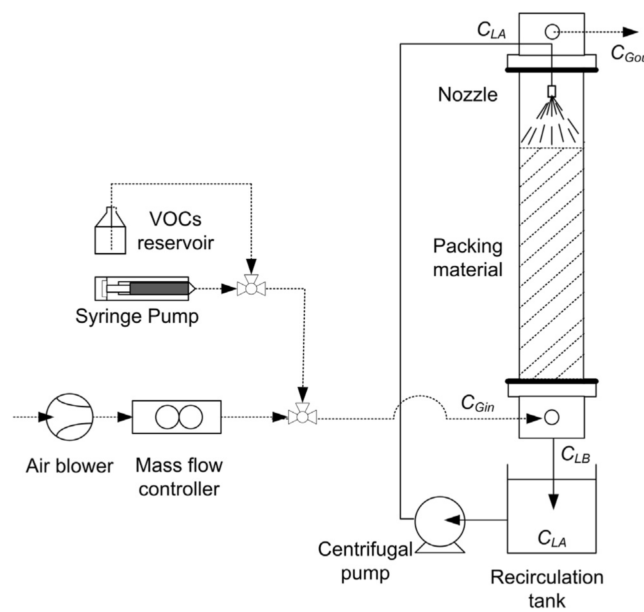

Fig. 1. Experimental set-up for the determination of the mass transfer coefficient of isopropanol.

Table 1
Characteristics of the packing materials.

Packing material		Diameter[a] (mm)	Density[a] (kg m^{-3})	Bed porosity[a] (%)	Specific surface area[a] (m^2 m^{-3})
PAS Winded Media[b]	Structured	–	–	93	410
Flexiring	Random	25	71	92	207[c]
Refilltech	Random	15	110.7	91	348

[a] Data provided by the suppliers.
[b] Packing material supplied by PAS Solutions BV.
[c] Larachi et al. (2008).