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Absorption of toluene in silicone oil: Effect of the solvent viscosity on hydrodynamics and mass transfer

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ABSTRACT

The purpose of this study was to compare toluene absorption performances using two PDMS of different viscosities ($\eta = 5$ and 50 mPa s, respectively) in terms of hydrodynamics and mass transfer. Three types of packing were tested in a counter-current packed gas–liquid contactor, Raschig rings, IMTP[®], and Flexipac[®]. Hydrodynamic results showed that the viscosity of PDMS 50 is not a hurdle to be used with IMTP[®] or Flexipac[®]; the pressure drop being around 288 Pa m^{-1} for Flexipac[®] at the flooding point ($F_G = 0.99 \text{ Pa}^{1/2}$; $L' = 4.95 \text{ kg m}^{-2} \text{ s}^{-1}$), which corresponds to an acceptable value for an industrial application. The determination of the loading zones showed that Raschig rings were not suitable for solvents having a high viscosity, such as PDMS 50; they resulted in high pressure drops if compared to IMTP[®] and Flexipac[®]. The mass transfer study showed that 100% removal efficiency can be reached for both PDMS using Flexipac[®]. For IMTP[®], the removal efficiency is limited to 88% in the presence of PDMS 50. As a result, PDMS 50 should be a relevant absorbing liquid for the removal of toluene in the absorption–biodegradation process, and Flexipac[®] packing should be preferred to IMTP[®].

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1. Introduction

Volatile organic compounds (VOCs) are air pollutants causing health and environmental problems. VOCs at low concentration in waste gas can be removed in bioreactors, but this technique has a poor efficiency when treating hydrophobic pollutants. One possible way to remove such pollutants is to use an absorption–biodegradation process (Fig. 1) combining an absorption step in a gas–liquid contactor and a

biodegradation step in a Two-Phase Partitioning Bioreactor (TPPB). A TPPB uses two immiscible liquid phases, the Non Aqueous Phase Liquid (NAPL) able to solubilize a high concentration of hydrophobic VOCs and an aqueous phase containing micro-organisms and nutrients (Daugulis, 2001; Malinowski, 2001; Muñoz et al., 2012). The VOC is then gradually transferred from the NAPL to the aqueous phase in order to be degraded by micro-organisms. Once regenerated, the NAPL is separated from water and recycled towards the absorber

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Nomenclature

a	specific surface ($\text{m}^2 \text{m}^{-3}$)
A_p	surface area (m^2)
C	VOC concentration (g m^{-3})
D	column diameter (m)
F_G	gas capacity factor ($\text{kg}^{1/2} \text{m}^{-1/2} \text{s}^{-1}$)
G	gas molar flow rate (mol s^{-1})
G'	gas mass flow rate ($\text{kg m}^{-2} \text{s}^{-1}$)
H	partition coefficient (dimensionless)
H'	partition coefficient ($\text{Pa m}^3 \text{mol}^{-1}$)
K_L	liquid mass transfer coefficient (m s^{-1})
$K_L a$	overall mass transfer coefficient (s^{-1})
L	liquid molar flow rate (mol s^{-1})
L'	liquid mass flow rate ($\text{kg m}^{-2} \text{s}^{-1}$)
M	molecular weight (kg mol^{-1})
Q_G	gas flow rate ($\text{m}^3 \text{s}^{-1}$)
Q_L	liquid flow rate ($\text{m}^3 \text{s}^{-1}$)
R	ideal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$)
T	temperature (K)
U_G	gas velocity (m s^{-1})
U_L	liquid velocity (m s^{-1})
V	packing volume (m^3)
Z	packing height (m)

Greek letters

ΔP	pressure drop (Pa)
ε	porosity (dimensionless)
η	dynamic viscosity (Pa s)
ρ	density (kg m^{-3})

Superscripts

*	equilibrium
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Subscripts

G	gas
in	inlet
L	liquid
out	outlet

(Quijano et al., 2009). A previous study showed that silicone oil (polydimethylsiloxane, PDMS) is an effective NAPL for this purpose as it is immiscible with water, not biodegradable, not toxic for microorganisms and has a high affinity for hydrophobic VOCs (Darracq et al., 2010). As PDMS is not soluble in water (Christine Stevens, 2001; Fendinger et al., 1997), the NAPL is continuously recycled in the system and the amount of PDMS discarded in the environment is negligible which makes this technology attractive. At the laboratory scale, PDMS 5, a silicone oil having a viscosity only 5 times higher than that of water, has been demonstrated to be valuable for TPPB application (Darracq et al., 2012a,b; Dumont et al., 2010–2012). However, PDMS 5 is volatile and some unidentified VOCs can be emitted in use, which may hinder the absorption process operation. As a result, the use of a PDMS of higher viscosity, such PDMS 50 (Guillerm et al., in press), is required. Since the solvent viscosity can influence the liquid distribution on the packing, the pressure drop in the contactor and the VOC diffusion coefficient, the use of a high-viscosity PDMS might have a considerable effect on the absorption performance and absorber design (Dumont et al., 2012). The purpose of this study was therefore to compare VOC absorption performances

using two PDMS of different viscosities ($\eta=5$ and 50 mPa s , respectively) in a counter-current packed gas–liquid contactor. Toluene was chosen as target pollutant. Three types of packing were used for this purpose: Raschig rings and IMTP[®], which are classical and modern random packings respectively, and Flexipac[®] which is a structured packing. Experimental results were compared in terms of hydrodynamics characterization (pressure drop and flooding point) and toluene mass transfer performances. Hydrodynamic performances obtained for each PDMS were also compared with water ($\eta=1 \text{ mPa s}$), considered as the liquid reference.

2. Material and methods

2.1. Chemical products

The two PDMS studied were referred as PDMS 5 and PDMS 50 in relation with their dynamic viscosity given by the manufacturers. PDMS 5 and PDMS 50 were respectively Rhodorsil 47V5 and Rhodorsil 47V50, provided by Bluestar Silicones Company. PDMS properties given by the manufacturers are presented in Table 1. PDMS are linear chains of various lengths comprising alternating silicon and oxygen atoms (the Si–O–Si siloxane bond; Fig. 2). The average molecular weight increases with the number of siloxane bonds.

Toluene (C_7H_8 ; CAS number: 108-88-3; purity $\geq 99.5\%$; molecular weight: 92.14 g mol^{-1} ; Sigma Aldrich) was selected as target VOC because this compound widely used in various industries is highly hydrophobic. The partition coefficient of toluene between PDMS and air was measured through a static headspace method described in Darracq et al. (2010). For the two PDMS studied, the partition coefficient values measured at 25°C are reported in Table 1. It can be considered that the partition coefficient does not vary with the PDMS viscosity. In other words, the affinity between toluene and PDMS is similar whatever the chain length, i.e. whatever the viscosity (Guillerm et al., In press). These partition coefficient values are significantly lower than that of toluene between water and air. Values reported in the literature range from 562 to $779 \text{ Pa m}^3 \text{mol}^{-1}$, whereas handbooks of physico-chemical properties give an average value of $680 \text{ Pa m}^3 \text{mol}^{-1}$ (Mackay et al., 2010). As a result, values of the partition coefficient ratio ($H'_{\text{water}}/H'_{\text{PDMS}}$) are from 235 to 250 indicating that the choice of these two PDMS for toluene absorption is fully justified.

2.2. Experimental set-up

Fig. 3 shows the experimental set-up used for toluene absorption. The inner diameter of the packed gas–liquid contactor is $D=0.12 \text{ m}$, and the total height of the packed bed is $Z=1 \text{ m}$ (packing volume $V=11.3 \text{ L}$). The packing was held in place top and bottom by grids. The column was topped with a bespoke droplet collector made in the laboratory. The polluted air was generated by injecting liquid toluene in an air stream by means of a syringe dispenser. The polluted air was then introduced into the bottom of the column and the liquid was flowed counter-currently. The air flow was regulated by means of a membrane valve placed after the fan and measured by a rotameter (GF Type SK 20 CH-8201 Schaffhausen Switzerland). The column was fed with PDMS by means of a centrifugal pump (Iwaki MD100, Iwaki America Inc.). The liquid flow rates was regulated by means of a valve and measured by a rotameter (GF type SK 11 CH-8201 Schaffhausen Switzerland).

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