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Intensification of volatile organic compound absorption in a compact wet scrubber at co-current flow

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Highlights

- Volatile organic compound absorption in water was investigated
- Butanol was removed up to 90% with a gas residence time of 20 ms
- The gas phase resistance could be more significant than the liquid phase resistance
- Using short scrubbers in series could be effective

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Abstract

Three volatile organic compounds (VOC) with no acidic or basic functions (butanol, butyraldehyde, methylethylketone), encountered at low concentrations in odorous effluents, were absorbed in water in a compact wet scrubber. This gas-liquid contactor consisted of a wire mesh packing structure where the gas phase flows at high velocity ($> 12 \text{ m s}^{-1}$). A very turbulent two-phase downward flow could be observed in the scrubber with dispersed fine droplets (around $10 \text{ }\mu\text{m}$). For compounds showing a good affinity for water, such as butanol, removal efficiencies up to 90% were measured for a short contactor length of 32 cm leading to a gas residence time of 20 ms. However, the removal efficiency of butyraldehyde, which is poorly soluble in water, ranged between 10 and 30%. Mass-transfer modeling was achieved and underlined that working with several small scrubbers in series, fed with an unloaded solution, is effective to improve the removal efficiency. The influences of the VOC/solvent affinity, the contactor length, and the mass-transfer and hydrodynamic parameters on the removal efficiency were evaluated through a sensitivity analysis.

Keywords

Volatile organic compound; co-current; scrubber; mass-transfer; absorption; gas treatment

1. Introduction

Waste and water treatments and many manufacturing industries induce gaseous emissions of volatile organic compounds (VOC) often related to odor nuisances. Many VOCs are harmful to the human health and the environment (Kampa and Castanas, 2008). Consequently, the legislations of industrialized countries become more and more drastic and impose to implement gas treatment processes to reduce VOC and odor emissions.

Among the different gas treatment technologies, wet scrubbing involving pollutant(s) mass-transfer in a liquid phase (either an aqueous solution or an organic solvent), is one of the most attractive technologies due to its simplicity and its potential high efficiency (Ruddy and Carroll, 1993; Khan and Ghoshal, 2000; Revah and Morgan-Sagastume, 2005; Schlegelmilch et al., 2005). On the one hand, organic solvents have a good affinity for VOC, but simultaneously induce higher investment and operating costs than water. Moreover, they must fulfill several constraining conditions (low partial pressure and viscosity, no toxicity, etc.) to be implemented and must be recycled (Darracq et al., 2012). On the other hand, the physical absorption efficiency in aqueous solution is massively influenced by the VOC solubility in water which depends on the VOC vapor pressure and on the activity coefficient (Biard et al., 2016).

During the last decade, a patented high void gas-liquid contactor (Aquilair PlusTM), operating at co-current and downward flows, has been developed for gas-liquid applications owing to its capacity to induce a high turbulence (Sanchez et al., 2007a; Sanchez et al., 2007c). This contactor consists of a wire mesh packing structure where the gas flows at high velocity ($> 12 \text{ m s}^{-1}$). The liquid phase, carried along by the gas stream, collides with the wire mesh and is dispersed into fine droplets (around $10 \text{ }\mu\text{m}$). The mass-transfer intensification and high interfacial area can be counterbalanced by a reduction of the contactor height and therefore of the gas residence time. Thus, the gas residence time and contactor height have been efficiently respectively reduced to less than 30 ms and 50 cm for H_2S and NH_3 treatments (Sanchez et al., 2007b; Couvert et al., 2008a; Biard et al.,

2010). The measured removal efficiencies (up to 95% at semi-industrial scale and up to 99% at laboratory scale) are similar to those obtained using classical packed columns in which a gas residence time around 1 s is required. The volumetric liquid and gas phase mass-transfer coefficients ($k_L a^\circ$, $k_G a^\circ$) have been measured and correlated to the liquid and gas superficial velocities and diffusion coefficients (Sanchez et al., 2007a; Couvert et al., 2008b; Biard et al., 2011).

This contactor belongs to a generation of intensified gas-liquid contactors, such as venturi-ejector, aero-ejector or static mixers, operated at co-current to reach high gas velocities and turbulences without flooding (De Billerbeck et al., 1999; Lee and Pang Tsui, 1999; Gamisans et al., 2002; Heyouni et al., 2002; Al Taweel et al., 2005; Couvert et al., 2006; Daubert-Deleris et al., 2006; Kies et al., 2006; Mi and Yu, 2012). They are effective alternatives to packed beds or spray columns traditionally used in wet scrubbing, with a high potential to treat acidic or basic compounds whose mass-transfer in water can be massively enhanced due to proton transfer reactions at appropriated pH (Biard and Couvert, 2013). In this case, very good removal efficiencies can be reached even with a low residence time (Gamisans et al., 2002; Sanchez et al., 2007b; Couvert et al., 2008a; Mi and Yu, 2012).

This compact scrubber is particularly appropriated to treat odorous effluents, which often contain ammonia and hydrogen sulfide (Burgess et al., 2001). An odor treatment processing chain would contain at least two scrubbers fed successively by an acidic aqueous solution and an alkaline chlorine solution to respectively target NH_3 and H_2S . Nonetheless, odorous effluents may contain a few ppmv of different VOCs, most of whom do not have either an acidic or a basic function. For the absorption of such organic compounds, the affinity for the selected solvent becomes a crucial point. For the moment, there is a lack of experimental data and models concerning the transfer of these VOCs in co-current scrubbers. Therefore, the goal of this study is to evaluate the compact scrubber potential for VOC absorption and to determine what level of the VOC removal efficiencies can be expected in an odor treatment processing chain. Furthermore, in co-current scrubbers, the mass transfer rate, proportional to the concentration gradient, decreases with the length since the gas-liquid equilibrium

can be reached before the outlet (Roustan, 2003). Thus, the removal efficiency evolution with the contactor height was simulated trying to optimize it.

Three odorous VOCs (butanol (BTOL), Butyraldehyde (BTA) and Methyl ethyl ketone (MEK)) were absorbed in a lab-scale version of the developed gas-liquid contactor. These three VOCs are currently involved in odor emissions, especially by composting facilities and have variable affinities for water (Krzymien et al., 1999; Dorado et al., 2014). These experiments add to the already published results on dimethyldisulfide (DMDS) (Biard et al., 2009) which were mainly focused on the potential of the peroxone process, combining H_2O_2 and O_3 in solution, to enhance the VOC mass-transfer. A mass-transfer model and a sensitivity analysis are developed to assess the influence of the operating conditions on the removal efficiency.

2. Material and methods

2.1 Gas-liquid contactor description

The lab-scale contactor, already described in the literature, consists of a transparent PVC pipe of 0.32 m length and 0.025 m inner diameter (volume of $1.57 \times 10^{-4} \text{ m}^3$), through which flow patterns can be observed (Couvert et al., 2008a). A picture of the scrubber is available as supplementary material. A low pipe diameter of 0.025 m was sufficient at the laboratory scale to treat up to $50 \text{ Nm}^3 \text{ h}^{-1}$ (Nm^3 refers to m^3 expressed in the standard conditions of temperature and pressure (STP), *i.e.* $T = 0^\circ\text{C}$, $P = 1 \text{ bar}$) of polluted air with liquid flow-rates in the range 30-150 L h^{-1} . The pipe diameter was successfully scaled up at 0.2 m to treat up to $2500 \text{ Nm}^3 \text{ h}^{-1}$ of gas in a waste water treatment plant (Biard et al., 2010). The contactor consists of a wire mesh (wires diameter = 0.6 mm and mesh size = 12.5 mm) packing structure offering a high void fraction (97.5%) and is devoted to turbulence promotion and droplets formation.

2.2 Pilot plant description

Outside air was pumped through a fan (Continental Industries, France), and cooled down by a tubular heat exchanger fed with water (Fig. 1). The volume gas flow-rate was measured with a float-type flowmeter (IDP provided by Bamo, France). The temperature (Testo, probe model 0613 12 12, France) and the pressure (Ashcroft T5500, Germany) were measured at the flowmeter outlet for the flow-rate correction. The pure liquid VOC was vaporized using a 10 mL gas tight syringe (SGE, Australia) and a syringe-pump (Kd Scientific 100, USA). Homogenization was achieved owing to a static mixer provided by Koflo (USA). An inlet VOC concentration of 5 ppmv, consistent with the concentration in odor treatment, was set. Tap water ($7.5 < \text{pH} < 8$), stored in a Nalgene tank, was pumped using a centrifugal pump (MD15FY, Iwaki, Japan) into the scrubber at co-current of the gas flow. The water flow-rate was measured and controlled by a float type flowmeter equipped with a valve provided by Brooks Instruments (USA). The gas-liquid mixture was separated in a vessel located at the contactor outlet.

115 All VOCs were purchased from Acros Organics (Belgium) with purities higher than 99%.

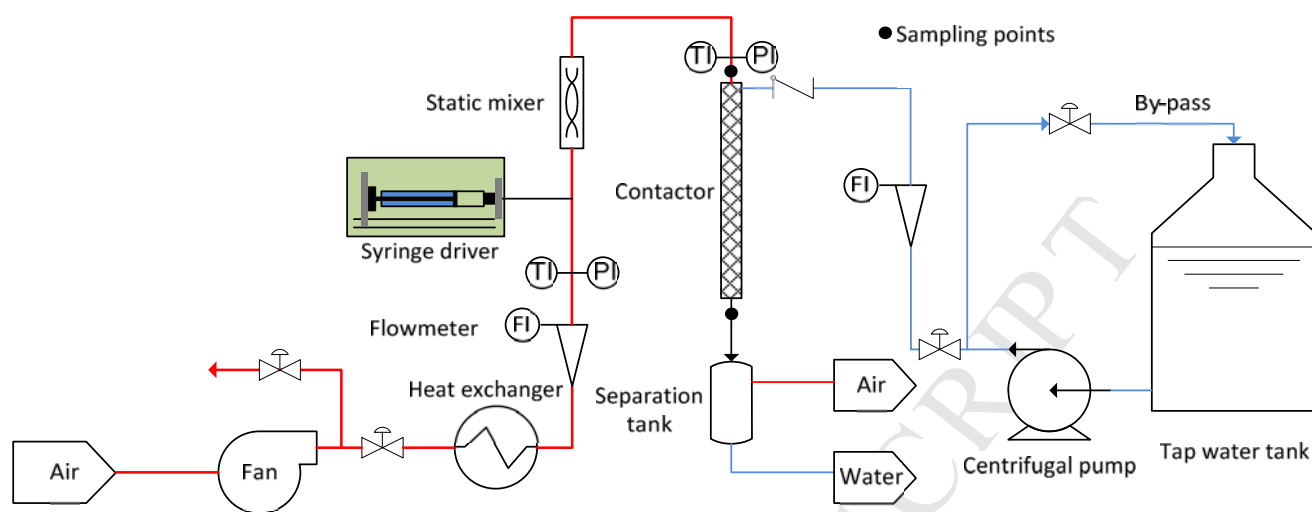


Fig. 1. Pilot plant process flow diagram.

2.3 Analytical methods

119 The single VOC were used for the experiments. The VOC gas concentration was measured at the
 120 contactor inlet and outlet with an on-line FID analyzer (JUM 190 L, Germany). VOC liquid
 121 concentrations were analyzed by a gas chromatograph equipped with a flame ionization detector by
 122 using the static headspace method (Biard et al., 2009).

3. Mass-transfer modeling

3.1 Introduction

The performance parameter was the removal efficiency, defined by Eq. (1):

$$Eff = \frac{C_{G,i} - C_{G,o}}{C_{G,i}} \quad (1)$$

C is the VOC concentration. The subscripts G, L, i and o refer respectively to the gas, the liquid, the inlet and the outlet. The removal efficiency is often considered as a pertinent performance parameter in the literature. This operation was assumed to be isobar (from 18 to 44 mbar of differential pressure between the inlet and the outlet) and isotherm since the temperatures of the gas and the liquid were close at the reactor inlet. The transfer of compounds with no basic or acidic function in water is based on physical absorption and is independent of the pH and the gas inlet concentration (Biard et al., 2009).

3.2 Mass-transfer modeling

Considering the low diameter/height ratio of the scrubber ($= 0.08$), the axial dispersion of the gas is particularly limited (*i.e* the diffusive transfer is negligible compared to the convective transfer) and the gas phase flow can be considered as a plug-flow. Indeed, as a first approximation, the contactor can be considered as an empty tube owing to its high void fraction and geometry (composed of channels) to determine an axial dispersion coefficient (D_{ax}) lower than $0.15 \text{ m}^2 \text{ s}^{-1}$ from a gas Reynolds number larger than 3×10^4 (Fogler, 1999). Therefore, the reactor Peclet number ($= U_{SG}Z/D_{ax}$ with Z the contactor length and U_{SG} the gas superficial velocity) would be larger than 40, allowing to confirm the plug-flow behavior of the gas phase (Fogler, 1999; Levenspiel, 1999). Moreover, the liquid is dragged as fine droplets by the gas at high velocity preventing liquid back-mixing. Therefore, assuming both gas and liquid co-current plug-flows, Eq. (2) is deduced from the mass-balance and the mass-transfer rate (Roustan, 2003):

$$F_G \times (C_{G,i} - C_{G,o}) = K_L a^\circ \frac{(C_L^{eq} - C_L)_i - (C_L^{eq} - C_L)_o}{\ln \frac{(C_L^{eq} - C_L)_i}{(C_L^{eq} - C_L)_o}} S \times Z \quad (2)$$

F_G is the gas flow rate ($\text{m}^3 \text{s}^{-1}$), S is the scrubber cross section (m^2) and $K_L a^\circ$ is the overall volumetric liquid mass-transfer coefficient (s^{-1}), deduced from the local volumetric gas ($k_G a^\circ$) and liquid ($k_L a^\circ$) mass-transfer coefficients (Roustan, 2003):

$$\frac{1}{K_L a^\circ} = \frac{1}{k_L a^\circ} + \frac{RT}{H k_G a^\circ} \quad (3)$$

a° is the interfacial area which increases with both gas and liquid superficial velocities (U_{SL} and U_{SG}) which induce higher turbulences (Sanchez et al., 2007a). In this lab-scale scrubber, the local volumetric gas ($k_G a^\circ$) and liquid ($k_L a^\circ$) mass-transfer coefficients can be correlated for any compounds to U_{SG} and U_{SL} and the solute gas and liquid diffusion coefficients ($D_{i,G}$ and $D_{i,L}$) respectively, according to Eq. (4) and (5) presented in a previous study (Biard et al., 2011):

$$k_L^i a^\circ (\text{s}^{-1}) = 1682 D_{i,L}^{0.5} U_{SG}^{0.800} U_{SL}^{0.172} \quad (4)$$

$$k_G^i a^\circ (\text{s}^{-1}) = 1230 D_{i,G}^{0.5} U_{SG}^{1.57} U_{SL}^{0.177} \quad (5)$$

Up to now, these correlations are specific of the lab-scale contactor used in this study and cannot be used for scale-up. A deeper mass-transfer study carried out with different contactor sizes and gas and liquid properties would be necessary to correlate the mass-transfer coefficients through the Sherwood number to the dimensionless Reynolds and Schmidt numbers.

In the Eq. (2), the liquid concentration at the equilibrium with the gas phase (C_L^{eq}) can be deduced from the gas concentration according to the Henry's law regarding the low VOC concentration in the liquid phase (infinite dilution assumption):

$$C_G = C_L^{eq} \times \frac{H}{RT} \quad (6)$$

166 H is the Henry's law constant of the considered VOC in water ($\text{Pa m}^3 \text{mol}^{-1}$). Using tap water at the
 167 inlet, $C_{L,i} = 0$. The mass balance on the VOC at the border of the contactor can be written as Eq. (7):

$$168 \quad F_G \times (C_{G,i} - C_{G,o}) = F_L C_{L,o} \Rightarrow C_{L,o} = \frac{F_G}{F_L} \times \text{Eff} \times C_{G,i} \quad (7)$$

169 F_L is the liquid flow rate ($\text{m}^3 \text{s}^{-1}$). According to Eqs (2), (6) and (7):

$$170 \quad F_G \times (C_{G,i} - C_{G,o}) = K_L a^\circ \frac{\frac{RTC_{G,i}}{H} - \left(\frac{RTC_{G,o}}{H} - \frac{F_G}{F_L} \times (C_{G,i} - C_{G,o}) \right)}{\frac{RTC_{G,i}}{H}} S \times Z \quad (8)$$

$$\ln \frac{\frac{RTC_{G,i}}{H}}{\frac{RTC_{G,o}}{H} - \frac{F_G}{F_L} \times (C_{G,i} - C_{G,o})}$$

171 Dividing both sides of Eq. (8) by $(C_{G,i} - C_{G,o})$ and using Eqs (1), Eq. (9) is finally obtained after
 172 rearrangement:

$$173 \quad \text{Eff} = \frac{A}{1+A} \left[1 - \exp \left(- \frac{(1+A) K_L a^\circ \times S \times Z}{F_L} \right) \right] \quad (9)$$

174 The absorption factor A (dimensionless) is defined according to Eq. (10) (Roustan, 2003; Benitez,
 175 2011):

$$176 \quad A = \frac{RT F_L}{H F_G} \quad (10)$$

177 In physical absorption at co-current, the concentration gradient, which is the mass-transfer driving
 178 force, decreases drastically from the inlet to the outlet. To limit the VOC accumulation in the
 179 scrubbing liquid between the inlet and the outlet, the absorption factor must be as large as possible
 180 by increasing the L/G ratio. It would imply to select a high liquid flow-rate to efficiently remove the
 181 VOC with a low affinity for the scrubbing liquid. However, the L/G ratio in this contactor must not
 182 exceed a limit value around 10 to limit the pressure drop and to insure a proper liquid dispersion of

183 the liquid (Couvert et al., 2008a). Eq. (9) can be rewritten to introduce the overall Height of Transfer
 184 Units (HTU_{OL} or HTU_{OG} in m) and Numbers of Transfer Units in the liquid and gas sides (NTU_{OL} or
 185 NTU_{OG}):

$$186 \quad Eff = \frac{A}{1+A} [1 - \exp(-(1+A)NTU_{OL})] \text{ with } NTU_{OL} = \frac{Z}{HTU_{OL}} \text{ and } HTU_{OL} = \frac{F_L}{K_L a^\circ S} \quad (11)$$

$$187 \quad Eff = \frac{A}{1+A} \left[1 - \exp\left(-\frac{(1+A)}{A} NTU_{OG}\right) \right] \text{ with } NTU_{OG} = \frac{Z}{HTU_{OG}} \text{ and } HTU_{OG} = \frac{RTF_G}{HK_L a^\circ S} \quad (12)$$

188 Eqs. (9)-(12) confirm that the removal efficiency is uninfluenced by the initial gas concentration as
 189 long as the Henry's law remains valid. However, it depends on the gas and liquid flow-rates through
 190 (i) the gas-liquid equilibrium quantified by the absorption factor, (ii), the mass-transfer and
 191 hydrodynamics within the scrubber ($K_L a^\circ$) and (iii) the gas residence time (through the term $S \times Z / F_G$ in
 192 the term NTU_{OG}). The liquid-to-gas mass flow-rates ratio (L/G), deduced from F_G , F_L and the gas and
 193 liquid densities, is often used by engineers and designers for performance assessment at comparable
 194 values of the absorption factor.

4. Results and discussion

4.1 Experimental results

The removal efficiency only depends on F_G and F_L in $\text{m}^3 \text{s}^{-1}$ (*i.e.* on the gas and liquid superficial velocities U_{SG} and U_{SL} in m s^{-1}) according to Eq. (9) at given temperature and pressure. Therefore, the other operating conditions (pH , $C_{G,i}$) were unvaried. Depending on U_{SG} and U_{SL} , the BTOL removal efficiency varied from 60% up to 90% according to Fig. 2 (a). Therefore, this compact scrubber is not solely effective using reactive systems, such as the ones involved during NH_3 or H_2S treatments (Couvert et al., 2008a), but is also appropriated to the physical absorption of VOCs with a good affinity for the selected solvent. In odor treatment, there is usually no specific minimal concentration to reach at the outlet of the air treatment process. However, high removal efficiencies are required in order to significantly decrease the odor nuisance.

The BTOL removal efficiency increased with L/G (*i.e.* F_L and U_{SL}) at a given U_{SG} , in agreement with both a mass-transfer improvement through a higher value of $K_L a^\circ$ (Eqs. (3)-(5)) and an absorption factor increasing (Eq. (10)). On the contrary, Eff decreased with U_{SG} at a given U_{SL} , showing that the mass-transfer improvement with U_{SG} (Eqs. (3)-(5)) is not counterbalanced by the gas residence time (Eq. (12)) and the absorption factor (Eq. (10)) decreasing. Nonetheless, the transferred flux of BTOL ($F_G \times (C_{G,i} - C_{G,o})$) increased with U_{SG} at a given U_{SL} and BTOL inlet concentration. The relative weight of $K_L a^\circ$, A and the gas residence time will be addressed through a sensitivity analysis (section 4.5). The BTOL concentration in water at the contactor outlet varied from 15 ppm to 4 ppm (Fig. 2 (b)) and increased when U_{SG} increased and U_{SL} decreased.

The gas flow-rate was solely set at $32.5 \text{ Nm}^3 \text{ h}^{-1}$ (corresponding to a gas superficial velocity of 17.4 m s^{-1}) to assess the BTA and MEK removal efficiencies. At this gas flow-rate, both the removal efficiency and the pressure drop were optimal even if the volumetric mass-transfer coefficients ($k_G a^\circ$ and $k_L a^\circ$), deduced from Eqs. (3)-(5), were lower (Table 1) (Biard et al., 2011). A lower gas superficial velocity was undesirable since the mass transfer coefficients dropped below 15 m s^{-1} (Couvert et al., 2008b).

Indeed, at 21.0 (23.0) m s^{-1} , the pressure drop increased by 49% (81%) whereas the volumetric mass-transfer coefficients in the gas ($k_G a^\circ$) and liquid ($k_L a^\circ$) phases increased by only 34% (55%) and 16% (25%) for a given liquid flow-rate.

Table 1. Pressure drop (ΔP), $k_L a^\circ$ and $k_G a^\circ$ values obtained at different U_{SG} for $U_{SL} = 0.029 \text{ m s}^{-1}$ ($F_L = 75 \text{ L h}^{-1}$).

	Unit	17.4 m s^{-1}	21.0 m s^{-1}	23.0 m s^{-1}
ΔP	mbar	80	119	145
$k_L a^\circ$	s^{-1}	0.279	0.325	0.350
$k_G a^\circ$	s^{-1}	185	248	286
L/G		1.7	1.4	1.2

The removal efficiency was strongly influenced by the VOC/solvent affinity (Fig 3 (a)) regarding the rather disappointing removal efficiencies of MEK (30-50%) and BTA (15-35%). BTA and MEK are respectively 15 and 18 times more volatile than BTOL according to their vapor pressures at 25°C leading to a poor solubility in water. Besides, the lower removal efficiency of BTA is due to its lower affinity for water than MEK. Thus, the VOC concentrations in water at the outlet varied from 2 ppm for BTA up to 12 ppm for BTOL (Fig 3 (b)). Dimethyldisulfide (DMDS) removal efficiency was particularly low (< 15%) due to its low affinity for water (Biard et al., 2009).

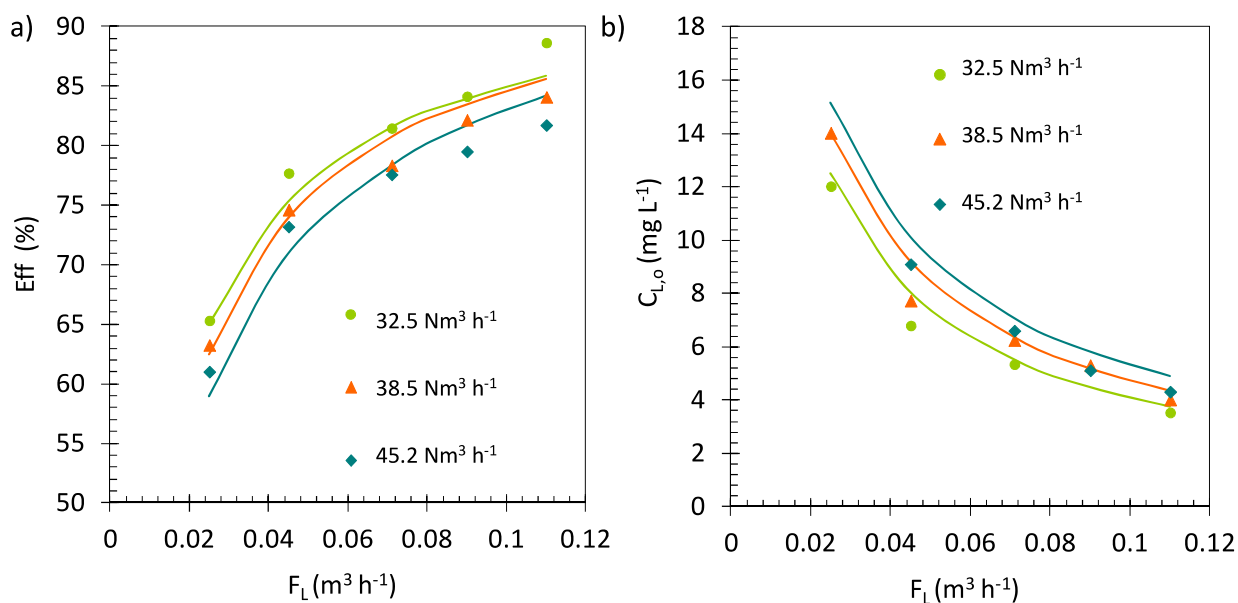


Fig 2. Evolution of Eff (a) and $C_{L,o}$ (b) with F_L (butanol case) for three different gas flow rate (32.5, 38.5 and 45.2 $\text{Nm}^3 \text{h}^{-1}$, corresponding to $U_{SG} = 17.4, 21.0$ and 23.0 m s^{-1} and $0.35 < L/G < 2.6$). The straight lines represent the predictions of the mass-transfer model (Eqs (7) and (9)).

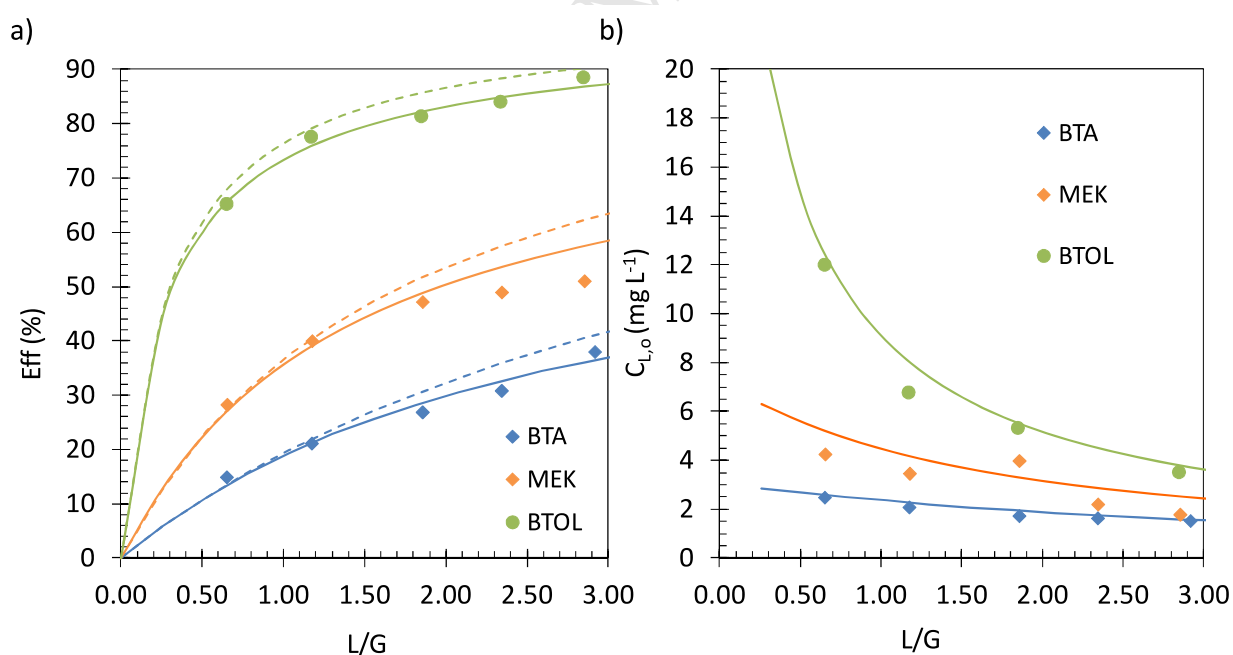


Fig 3. Evolution of Eff (a) and $C_{L,o}$ (b) with the L/G ratio ($F_G = 32.5 \text{ Nm}^3 \text{h}^{-1}$, $0.025 \text{ m}^3 \text{h}^{-1} < F_L < 0.120 \text{ m}^3 \text{h}^{-1}$). The straight lines represent the predictions of the mass-transfer model (Eqs (7) and (9)). The dash lines represent the limit removal efficiency (Eq. (14)).

4.2 Mass-transfer modeling assessment

The good agreement between the model (using the diffusion coefficients and Henry's law constants summarized in Table 2 (Perry and Green, 1997; Roustan, 2003; Sander, 1999)), which do not require any fitted variable, and the experimental data was confirmed with an average relative error ranging between 2.4 % for BTOL up to 9.4% for BTA (Table 2, Fig. 2 (a) and Fig. 3 (a)). The modeled liquid concentrations (calculated from Eqs. (7) and (9)) fitted the measured ones (Fig. 2 (b) and Fig. 3 (b)) confirming the mass-balance agreement. The gas-phase relative mass-transfer resistance ($0 < R_G < 1$) was evaluated through Eq. (13) (Hoffmann et al., 2007; Rejl et al., 2009):

$$R_G = 1 - R_L = 1 - \left(1 + \frac{RTk_L a^\circ}{Hk_G a^\circ} \right)^{-1} \quad (13)$$

Table 2. Summary of the values of $D_{i,L}$, $D_{i,G}$ and H used to determine Eff with Eq. (9) and of the average relative error and R_G values (Eq. (13)).

	Unit	BTOL	MEK	BTA
$D_{i,G}^a$	$m^2 s^{-1}$	0.88×10^{-5}	0.90×10^{-5}	0.90×10^{-5}
$D_{i,L}^b$	$m^2 s^{-1}$	0.85×10^{-9}	0.88×10^{-9}	0.88×10^{-9}
H at 298 K ^c	$Pa m^3 mol^{-1}$	0.90	5.3	12.6
Average relative error ^d		2.4%	7.6%	9.4%
R_G		$\approx 81\%$	$\approx 41\%$	$\approx 24\%$

^a Calculated with the Fuller et al. correlation cited by Perry and Green (1997) and Roustan (2003).

^b Calculated with the Wilke and Chang correlation cited by Perry and Green (1997) and Roustan (2003).

^c From Sander (1999)

^d The average relative error is the average of the relative errors between the experimental values of Eff and the values deduced from the model (Eq. (9)).

R_G allows to assess the weight of the gas-phase resistance compared to the liquid phase resistance. In the literature, the gas phase resistance is often neglected by assuming that the whole resistance is located in the liquid phase following erroneous intuitions. Even if the volumetric gas-phase mass-

transfer coefficient ($k_G a^\circ$) order of magnitude is particularly high in this compact scrubber (larger than 100 s^{-1}), the gas-phase resistance must not be neglected, especially for compounds presenting a good affinity with water such as BTOL. Indeed, the values of R_G were in the range 24-81% emphasizing that the gas phase resistance could be even more significant than the liquid phase resistance (Table 2).

4.3 Influence of the contactor length - combination of scrubbers in series

Mass-transfer modeling can be advantageously used to assess the influence of the different operating conditions, especially since the scrubber works at co-current which means that equilibrium can be reached. To optimize the gas residence time, a compromise needs to be found between the length of the scrubber and the gas superficial velocity (*i.e* the gas flow-rate and the diameter), taking into account that the selection of the gas superficial velocity is crucial to limit the pressure drop and to maximize the mass-transfer performances. According to Eq. (9), the limit removal efficiency (Eff_{lim}) corresponding to an infinite NTU depends only on the absorption factor A :

$$Eff_{lim} = \frac{A}{1 + A} \quad (14)$$

Especially at low L/G value, the measured removal efficiency was close to Eff_{lim} , represented on Fig. 3 (a) by the dash lines. Therefore, the experimental scrubber length of 32 cm sufficed at co-current to approach or reach the equilibrium, depending on F_L and F_G , as proved by the plateau of the plot representing the simulated removal efficiency (through Eq. (9)) evolution with the length of the contactor (Fig. 4).

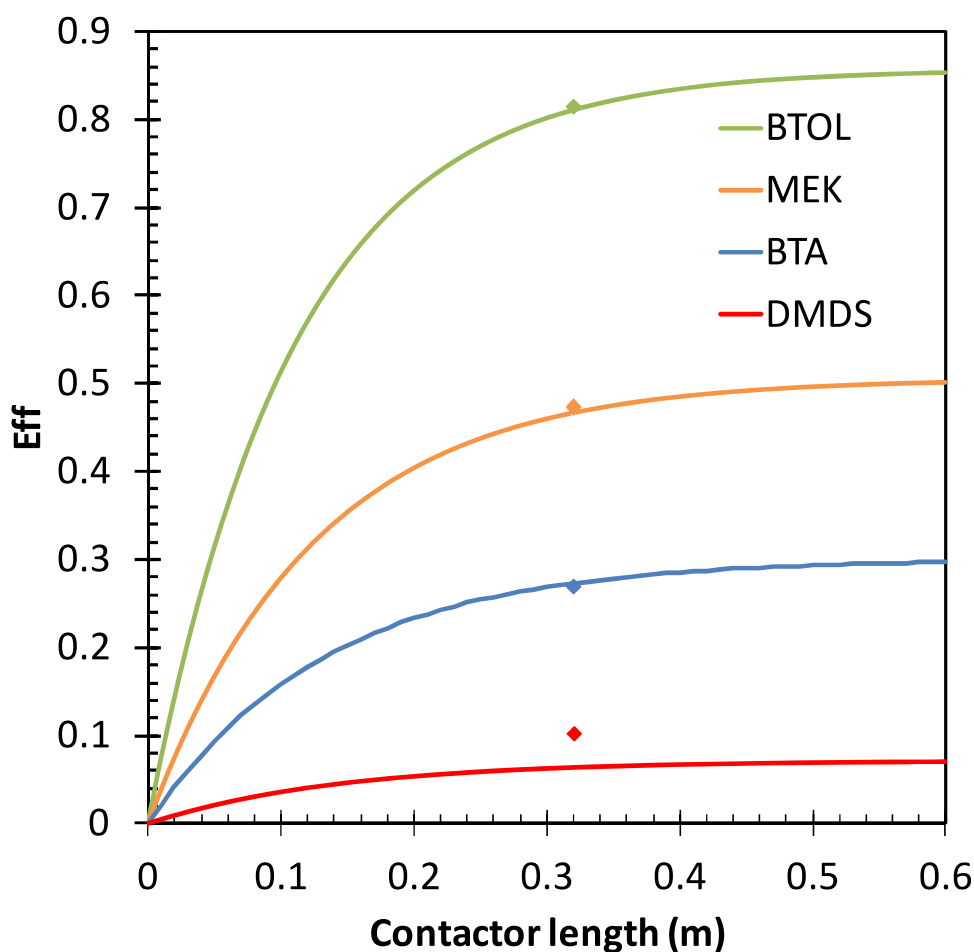


Fig 4. Simulation of the evolution of the removal efficiency (calculated according to Eq. 9) with the scrubber length (straight lines). $F_G = 32.5 \text{ Nm}^3 \text{ h}^{-1}$, $F_L = 75 \text{ L h}^{-1}$ ($L/G = 1.8$). The points correspond to the experimental data. The data for DMDS are extracted from Biard et al. (2011).

Therefore, the combination of several short contactors in series, each fed with tap water, is more effective than only one contactor with the same total height and the same L/G ratio, as proved by the simulations performed on BTOL using Eq. (9) (Fig. 5). Owing to the replacement of the loaded solution by unloaded tap water after a few centimeters of contact, this configuration allows to limit the solute accumulation in the liquid phase and to maximize the concentration gradient. With only three scrubbers of 15 cm (total residence time of 25 ms), it is possible to reach a removal efficiency of BTOL of 99% proving the potential of this scrubber for VOC removal. The total pressure drop should be almost identical. Nonetheless, this configuration implies to discharge the loaded solution

for each scrubber separately and introduce an unloaded solution for each scrubber. More water would be polluted but at a lower concentration. A regeneration unit would be necessary to limit the water consumption and recycle it.

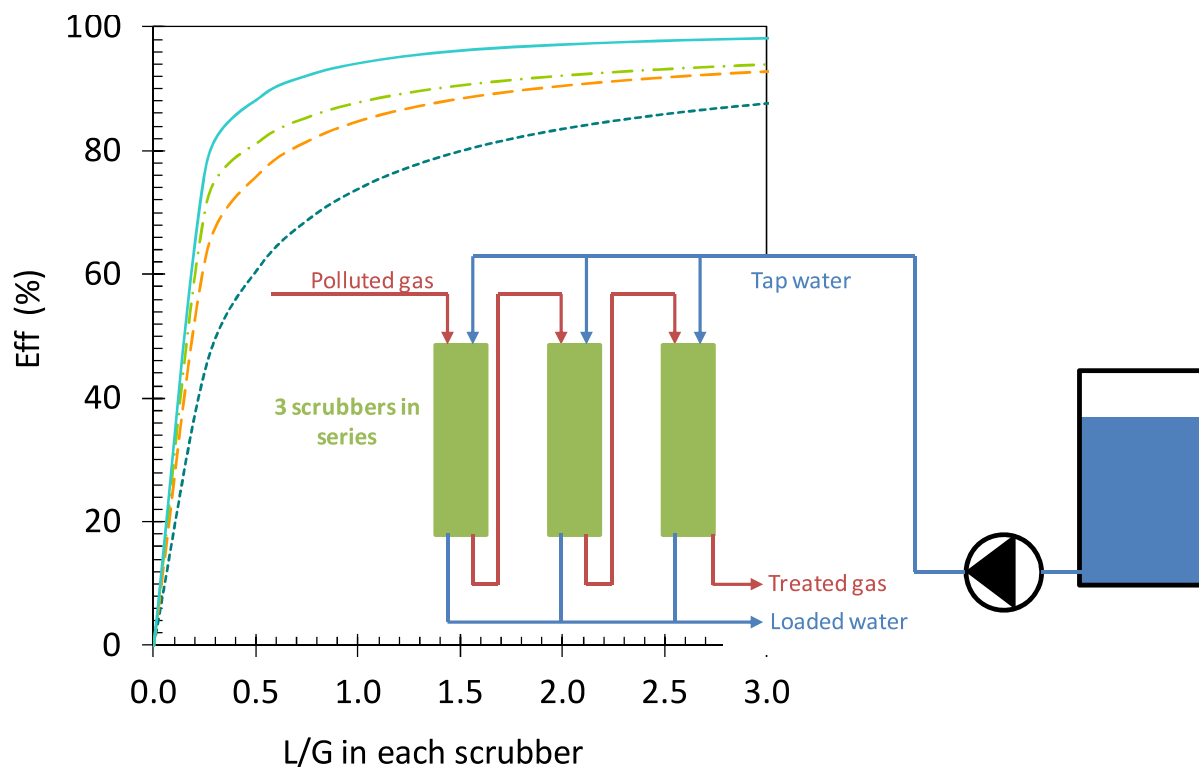


Fig 5. Simulation of the VOC removal efficiency evolution with the L/G ratio for various combinations of scrubbers in series fed with unloaded water. $F_G = 32.5 \text{ Nm}^3 \text{ h}^{-1}$, $25 \text{ L h}^{-1} < F_L < 120 \text{ L h}^{-1}$.

4.4 Comparison between a combination of short scrubbers in series and a packed column

Two scrubbers in series, each fed with unloaded water (at 70 L h^{-1} for each scrubber), were compared to a packed column at counter-current fed with a liquid flow rate of 140 L h^{-1} to achieve a removal efficiency of BTOL of 90% (Table 3). Thus, the liquid consumption was identical for the two systems. A dumped packing (Hiflow-Ring) with a low size (2.0 mm), adapted to the low gas flow-rate ($F_G = 32.5 \text{ Nm}^3 \text{ h}^{-1}$) simulated, was selected. This packing exhibits a high surface area of $286.2 \text{ m}^2 \text{ m}^{-3}$, allowing a comparison of the compact scrubber with an efficient packing. The loading ($U_{SG,lo} = 1.08 \text{ m s}^{-1}$) and

flooding ($U_{SG,fl} = 1.56 \text{ m s}^{-1}$) gas superficial velocities, the liquid hold-up ($\eta_L = 8.6\%$), the interfacial area ($a^\circ = 91.8 \text{ m}^2 \text{ m}^{-3}$) and both the gas and liquid film mass-transfer coefficients ($k_L = 1.84 \times 10^{-4} \text{ m s}^{-1}$ and $k_G = 6.90 \times 10^{-2} \text{ m s}^{-1}$) have been calculated using the correlations of Billet and Schultes (Billet and Schultes, 1991, 1993a, b; Billet and Schultes, 1995, 1999). The selected packing has been previously fully characterized by Billet-Schultes allowing to determine all these characteristics with a high level of confidence.

Table 3. Comparison of a combination of two compact co-current scrubbers in series and a counter-current packed column to reach a removal efficiency of BTOL of 90%. The packed column is fed with 140 L h^{-1} of tap water whereas the two scrubbers in series are each fed with 70 L h^{-1} of tap water. The water at the outlet of the first scrubber is separated to introduce unloaded water instead.

Operating conditions								
Eff	F_L (L h ⁻¹)		F_G (Nm ³ h ⁻¹)		P (bar)	T (°C)		
90%	140		32.5		1	20		
Scrubbers design								
Contactor	$10^4 \times k_L$ (m s ⁻¹)	$10^2 \times k_G$ (m s ⁻¹)	a° (m ⁻¹)	$10^3 \times K_L a^\circ$ (s ⁻¹)	HUT_{OG} (m)	Z (m)	τ (s)	ΔP (mbar)
2 compact scrubbers	1.42	9.43	2103	56.3	0.11	2×0.15	0.018	26
Packed column	1.84	6.90	91.8	1.55	0.27	0.54	0.43	3.3
Packing characteristics and hydrodynamics								
$U_{SG,lo}$ (m s ⁻¹)	$U_{SG,fl}$ (m s ⁻¹)	U_{SG} (m s ⁻¹)	D (cm)	η_L (%)	Packing	Material	Size (mm)	
1.08	1.56	1.25	6.9	8.6	Hiflow Ring	Ceramic	2.0	

The overall height of a transfer unit in the gas phase (HUT_{OG}) is advantageously 2.5 times lower in the compact scrubbers in series than in the packed column, resulting mainly from an interfacial area (calculated according to a correlation developed earlier (Biard, 2009)) around 20 times higher in the short scrubbers and a cross-section around 8 times lower. Therefore, the residence time (τ), the total scrubber volume and the total contactor height (Z) were respectively 24 times, 27 times and 1.8 times lower using the two compact scrubbers affecting favorably the investment costs. Nonetheless, these good mass-transfer performances using the compact scrubbers were counterbalanced by a higher energy footprint since the pressure drop (calculated according to Biard, 2009) was 8 times

higher than the one of the packed column. Firstly, the wire mesh packing structure of the compact scrubber can still be improved to decrease the pressure drop, for example by inserting spacers between the wire mesh layers. Secondly, these compact co-current scrubbers would be more easily applied on the field than a bulky packed column, allowing to implement them closer to the odorous sources and then to reduce the linear pressure drop until the treatment unit. Besides, this wire mesh packing structure offers a higher potential for the treatment of reactive compounds, such as NH_3 or H_2S which can be transferred respectively on an acidic aqueous solution or an alkaline chlorine solution (Couvert et al., 2008a), than for non-reactive compounds absorption. Usually, odorous effluents would be treated in a processing chain containing at least two scrubbers to respectively target NH_3 and H_2S . In that case, the H_2S , NH_3 and VOC removal achieved in these two scrubbers would be enough to significantly reduce the odor nuisance.

4.5 Sensitivity analysis

To assess the influence of the different inputs (I) on the output (O , here the removal efficiency) and to gain information on the model, a simple and local sensitivity analysis method based on the elasticity index (EI) calculation has been achieved (Mandel, 2010; Vilmain et al., 2014):

$$EI_I^O = \frac{I}{O} \left(\frac{\partial O}{\partial I} \right) \quad (15)$$

The sensitivity of the output to the input is shortened when EI tends toward 0. The inputs are:

- The liquid and gas flow-rates F_L and F_G
- The Henry's law constant H
- The contactor length Z

The output Eff depends to a major extent on the inputs F_G , F_L and H through their influence on the absorption factor (A) and the residence time (except H) than through their influence on the mass-transfer ($K_L a^\circ$). Therefore, the influences of A and $K_L a^\circ$ were directly evaluated instead. The Elasticity Index was evaluated vs. the Henry's law constant value and for two scrubber sizes (10 and 30 cm)

(Fig. 6). For the compounds with a high affinity with the scrubbing liquid (low Henry's law constant), the removal efficiency depends very significantly on the mass-transfer performances ($6.5 \leq EI_{K_L a^\circ} \leq 16$ for $0.1 < Z < 0.3$ when $H = 0.5 \text{ Pa m}^3 \text{ mol}^{-1}$). On the contrary, for the compounds with a low affinity for the scrubbing liquid (high Henry's law constant), an improvement of the absorption factor (by decreasing the gas superficial velocity and/or increasing the liquid superficial velocity) is required to improve the removal efficiency. Indeed, in that case the removal efficiency becomes almost insensitive to $K_L a^\circ$ (a plateau with $EI_{K_L a^\circ}$ around 0.1 is reached) whereas it significantly depends on the absorption factor ($EI_A \approx 1$ when $H = 50 \text{ Pa m}^3 \text{ mol}^{-1}$). When a scrubber of 30 cm is simulated, in which the equilibrium is almost reached, the removal efficiency is poorly sensitive to the scrubber length ($EI_Z < 0.5$). On the contrary, for a short scrubber, the removal efficiency depends significantly on the scrubber length ($0.5 < EI_Z < 3.5$ depending on H). This sensitivity analysis provides guidance about the parameters which should be optimized to improve the removal efficiency depending on the VOC solubility in water.

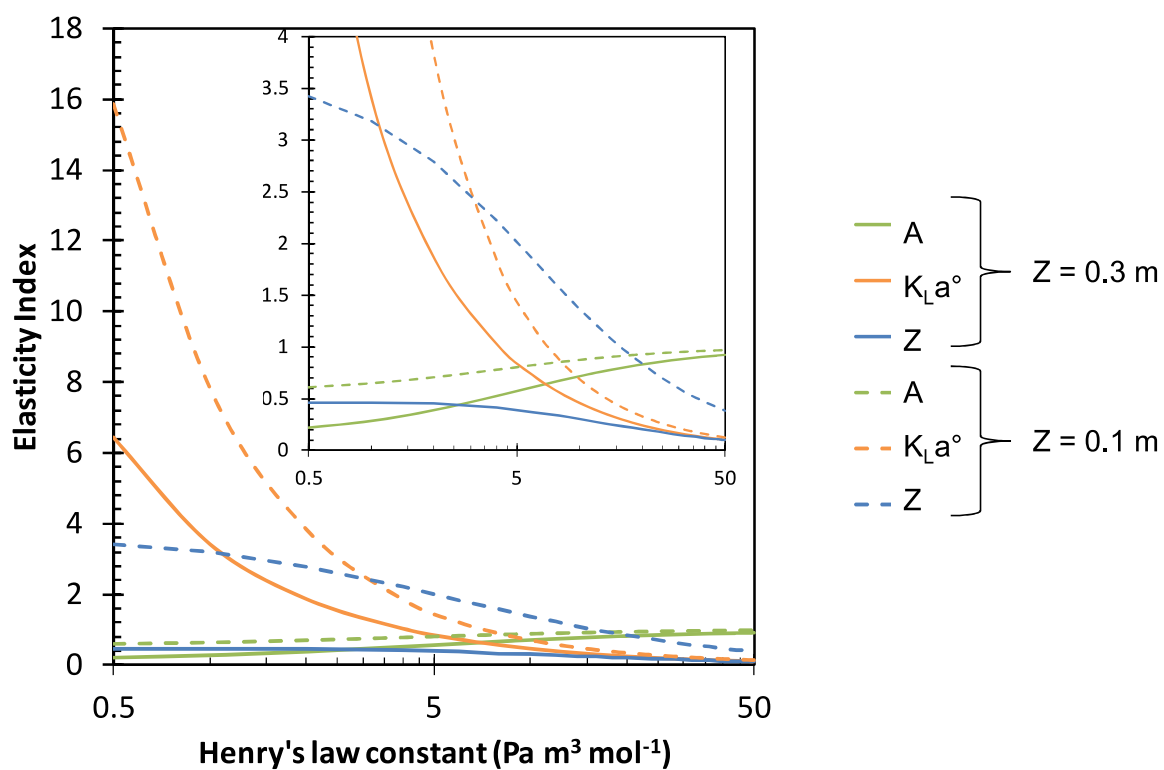


Fig 6. Elasticity index calculation ($Eff = output$) evolution with the Henry's law constant for different inputs (A , $K_L a^\circ$, Z) and for 2 scrubber lengths ($Z = 0.1$ and 0.3 m). $F_G = 32.5 \text{ Nm}^3 \text{ h}^{-1}$ and $F_L = 75 \text{ L h}^{-1}$.

4. Conclusion

VOC removal in a compact wet scrubber was investigated at low concentrations encountered in odorous effluents. The scrubber, consisting of a wire mesh packing structure, was operated at co-current and downward flows at a large velocity higher than 12 m s^{-1} allowing to decrease the contactor diameter. Owing to the large interfacial area obtained, the contactor length and the gas residence time were only respectively 32 cm and less than 30 ms.

The experimental results underlined the strong influence of the VOC affinity with the scrubbing liquid, which is linked to the VOC partial pressure and activity coefficient. The VOC affinity was quantified through the VOC partition coefficient at infinite dilution (Henry's law constant). For butanol, which has a good affinity for water owing mainly to a rather low vapor tension, removal efficiencies up to 90% were reached. Nonetheless, for VOC with a lower affinity for water such as butyraldehyde, the removal efficiency obtained in one contactor is limited. The mass-transfer modeling demonstrated that the mass-transfer rate decreased rapidly in the scrubber and that the last centimeters were poorly active.

Therefore, a combination of short scrubbers in series was proposed as an effective alternative to improve the removal efficiency. A combination of two compact co-current scrubbers of 15 cm was compared to a packed column to achieve a removal efficiency of BTOL of 90%. A mass-transfer rate 36 times higher in the two compact co-current scrubbers, counterbalanced by a pressure drop 8 times higher, was calculated. Nonetheless, these compact scrubbers would be more easily applied on the field, allowing to implement them closer to the odorous sources and then to reduce the linear pressure drop until the treatment unit. Furthermore, odorous effluents are usually treated in a processing chain which involved at least two scrubbers to target NH_3 (acidic aqueous solution) and H_2S (alkaline chlorine solution). Thus, no additional scrubber to target specifically VOCs would be necessary since a sufficient odor nuisance reduction can be expected from these two scrubbers. A sensitivity analysis, a particularly useful tool for the design of co-current contactors, was addressed

to provide guidance. To ensure the sustainability of the process, the scrubbing liquid must be regenerated, which could be achieved with the help of an advanced oxidation process to prevent VOC accumulation in the liquid phase (Tokumura et al., 2008; Biard et al., 2009, 2011; Tokumura et al., 2012). Due to its high selectivity, the use of an aqueous solution is restricted to the removal of compounds with a high affinity for water (H lower than around $5 \text{ Pa m}^3 \text{ mol}^{-1}$) or for acidic or basic VOCs. Water could be wisely replaced by organic solvents possessing low or moderate viscosities, such as some silicone oils or DEHA (Darracq et al., 2010; Biard et al., 2016). The applications of this contactor are not limited to VOC and odor treatments, flue gas desulfurization, NO_x treatment, CO_2 capture or stripping are also feasible options. Finally, the wire mesh packing structure can still be improved to decrease the pressure drop, for example by inserting spacers between wire mesh layers.

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6. Glossary

- 409 **6. Glossary**
- 410 α° : interfacial area relative to the packing volume ($\text{m}^2 \text{m}^{-3}$)
- 411 A : absorption factor (dimensionless)
- 412 C : VOC concentration (mol m^{-3} in the calculation)
- 413 D : column diameter (m)
- 414 D_{ax} : axial dispersion coefficient ($\text{m}^2 \text{s}^{-1}$)
- 415 $D_{i,G}$ ($D_{i,L}$): diffusion coefficient at infinite dilution of a solute in the gas phase (liquid phase) ($\text{m}^2 \text{s}^{-1}$)
- 416 Eff : removal efficiency
- 417 EI : Elasticity Index
- 418 F : flow-rate ($\text{m}^3 \text{s}^{-1}$ or $\text{Nm}^3 \text{s}^{-1}$)
- 419 H : Henry's law constant ($\text{Pa m}^3 \text{mol}^{-1}$)
- 420 HTU : Height of a Transfer Unit (m)
- 421 I : input
- 422 k_G : gas-film mass-transfer coefficient (m s^{-1})
- 423 k_L : liquid-film mass-transfer coefficient (m s^{-1})
- 424 $k_G \alpha^\circ$: local volumetric gas-side mass-transfer coefficient (s^{-1})
- 425 $k_L \alpha^\circ$: local volumetric liquid-side mass-transfer coefficient (s^{-1})
- 426 $K_L \alpha^\circ$: overall volumetric liquid-side mass-transfer coefficient (s^{-1})
- 427 L/G : liquid-to-gas mass flow-rate ratio (dimensionless)
- 428 NTU : Number of Transfer Units
- 429 O : output
- 430 P : absolute pressure in the reactor (Pa)
- 431 R_L : relative mass-transfer resistance in the liquid phase (%)
- 432 S : scrubber cross-section
- 433 T : temperature of the reactor ($^\circ\text{C}$ or K)
- 434 U : fluid velocity (m s^{-1})

435 Z: contactor height (m)

436

437

438 **Greek letters:**

439 ΔP : pressure drop (Pa or mbar)

440 τ : gas residence time (s)

441 η_L : liquid hold-up (%)

442

443 **Superscripts:**

444 eq: at the equilibrium

445

446 **Subscripts:**

447 fl: at the flooding point

448 G: relative to the gas

449 i : at the scrubber inlet

450 L: relative to the liquid

451 lim: relative to the limit removal efficiency

452 lo: at the loading point

453 o: at the scrubber outlet

454 O: overall

455 S: superficial (velocity)

References

- Al Taweel, A.M., Yan, J., Azizi, F., Odedra, D., Gomaa, H.G., 2005. Using in-line static mixers to intensify gas-liquid mass transfer processes. *Chem. Eng. Sci.* 60, 6378-6390.
- Benitez, J., 2011. Principles and Modern Applications of Mass Transfer Operations. John Wiley & Sons, Hoboken.
- Biard, P.-F., 2009. Contribution au développement d'un procédé de lavage chimique compact. Traitement du sulfure d'hydrogène par le chlore à l'échelle semi-industrielle et de COV odorants par oxydation avancée O_3/H_2O_2 à l'échelle du laboratoire. PhD Thesis, University of Rennes 1, Rennes, <https://hal.archives-ouvertes.fr/hal-01254796v1>, access date : January 2017.
- Biard, P.-F., Coudon, A., Couvert, A., Giraudet, S., 2016. A simple and timesaving method for the mass-transfer assessment of solvents used in physical absorption. *Chem. Eng. J.* 290, 302-311.
- Biard, P.-F., Couvert, A., 2013. Overview of mass transfer enhancement factor determination for acidic and basic compounds absorption in water. *Chem. Eng. J.* 222, 444-453.
- Biard, P.-F., Couvert, A., Renner, C., Levasseur, J.-P., 2009. Assessment and optimisation of VOC mass transfer enhancement by advanced oxidation process in a compact wet scrubber. *Chemosphere* 77, 182-187.
- Biard, P.-F., Couvert, A., Renner, C., Levasseur, J.-P., 2010. Wet scrubbing intensification applied to hydrogen sulphide removal in waste water treatment plant. *Can. J. Chem. Eng.* 88, 682-687.
- Biard, P.-F., Couvert, A., Renner, C., Levasseur, J.-P., 2011. Intensification of VOC gas-liquid mass transfer in a compact scrubber using the peroxone process: kinetic study and hydroxyl radical tracking. *Chemosphere* 85, 1122-1129.
- Billet, R., Schultes, M., 1991. Modelling of pressure drop in packed columns. *Chem. Eng. Technol.* 14, 89-95.
- Billet, R., Schultes, M., 1993a. A physical model for the prediction of liquid hold-up in two-phase countercurrent columns. *Chem. Eng. Technol.* 16, 370-375.

- 481 Billet, R., Schultes, M., 1993b. Predicting mass transfer in packed columns. Chem. Eng. Technol. 16, 1-
482 9.
- 483 Billet, R., Schultes, M., 1995. Fluid dynamics and mass transfer in the total capacity range of packed
484 columns up to the flood point. Chem. Eng. Technol. 18, 371-379.
- 485 Billet, R., Schultes, M., 1999. Prediction of mass transfer columns with dumped and arranged
486 packings: updated summary of the calculation method of Billet and Schultes. Chem. Eng. Res. Des.
487 77, 498-504.
- 488 Burgess, J.E., Parsons, S.A., Stuetz, R.M., 2001. Developments in odour control and waste gas
489 treatment biotechnology: a review. Biotechnol. Adv. 19, 35-63.
- 490 Couvert, A., Sanchez, C., Charron, I., Laplanche, A., Renner, C., 2006. Static mixers with a gas
491 continuous phase. Chem. Eng. Sci. 61, 3429-3494.
- 492 Couvert, A., Sanchez, C., Laplanche, A., Renner, C., 2008a. Scrubbing intensification for sulphur and
493 ammonia compounds removal. Chemosphere 70, 1510-1517.
- 494 Couvert, A., Sanchez, C., Laplanche, A., Renner, C., Levasseur, J.P., 2008b. Design of a new compact
495 scrubber for deodorisation. Chem.Eng. Proc.: Process Intensification 47, 1793-1798.
- 496 Darracq, G., Couvert, A., Couriol, C., Amrane, A., Le Cloirec, P., 2012. Removal of Hydrophobic
497 Volatile Organic Compounds in an Integrated Process Coupling Absorption and Biodegradation—
498 Selection of an Organic Liquid Phase. Water, Air, & Soil Pollution 223, 4969-4997.
- 499 Darracq, G., Couvert, A., Couriol, C., Amrane, A., Thomas, D., Dumont, E., Andres, Y., Le Cloirec, P.,
500 2010. Silicone oil: An effective absorbent for the removal of hydrophobic volatile organic
501 compounds. J. Chem. Technol. Biotechnol. 85, 309-313.
- 502 Daubert-Deleris, I., Hoffmann, P.A., Fonade, C., Maranges, C., 2006. Hydrodynamic and mass transfer
503 performance of a new aero-ejector with its application to VOC abatement. Chem. Eng. Sci. 61, 4982-
504 4993.
- 505 De Billerbeck, G., Condoret, J.S., Fonade, C., 1999. Study of mass transfer in a novel gas-liquid
506 contactor : the aero ejector. Chem. Eng. J. 72, 185-193.

- 507 Dorado, A.D., Husni, S., Pascual, G., Puigdemívol, C., Gabriel, D., 2014. Inventory and treatment of
508 compost maturation emissions in a municipal solid waste treatment facility. *Waste Management* 34,
509 344-351.
- 510 Fogler, H.S., 1999. *Elements of Chemical Reaction Engineering*. Prentice-Hall, Upper Saddle River.
- 511 Gamisans, X., Sarra, M., Lafuente, F.J., 2002. Gas pollutants removal in a single- and two-stage
512 ejector-venturi scrubber. *J. Hazard. Mat.* 90, 251-266.
- 513 Heyouni, A., Roustan, M., Do-Quang, Z., 2002. Hydrodynamics and mass transfer in gas-liquid flow
514 through static mixers. *Chem. Eng. Sci.* 57, 3325-3333.
- 515 Hoffmann, A., Mackowiak, J., Gorak, A., Haas, M., Loning, J., Runowski, T., Hallenberger, K., 2007.
516 Standardization of mass transfer measurements: a basis for the description of absorption processes.
517 *Chem. Eng. Res. Des.* 85, 40-49.
- 518 Kampa, M., Castanas, E., 2008. Human health effects of air pollution. *Environ. Pollut.* 151, 362-367.
- 519 Khan, F., I., Ghoshal, A., Kr., 2000. Removal of Volatile Organic Compounds from polluted air. *J. Loss*
520 *Prevent. Proc.* 13, 527-545.
- 521 Kies, F.K., Benadda, B., Otterbein, M., 2006. Hydrodynamics, Mass Transfer and Gas Scrubbing in a
522 Co-current Droplet Column Operating at High Gas Velocities. *Chem. Eng. Technol.* 29, 1205-1215.
- 523 Krzymien, M., Day, M., Shaw, K., Zaremba, L., 1999. An investigation of odors and Volatile Organic
524 Compounds released during composting. *J. Air Waste Manage. Assoc.* 49, 804-813.
- 525 Lee, S.Y., Pang Tsui, Y., 1999. Succeed at gas/liquid contacting. *Chem. Eng. Prog.* 95, 23-49.
- 526 Levenspiel, O., 1999. *Chemical Reaction Engineering- Third edition*. John Wiley & Sons, New York.
- 527 Mandel, P., 2010. *Modelling Ozonation Processes for Disinfection By-product Control in Potable*
528 *Water Treatment : from Laboratory to Industrial Units*. PhD Thesis. Université de Rennes 1, Rennes,
529 <https://hal.archives-ouvertes.fr/tel-00564767v1>, access date : January 2017.

- 530 Mi, T., Yu, X.M., 2012. Dust removal and desulphurization in a novel venturi scrubber. Chem. Eng.
531 Proc.: Process Intensification 62, 159-167.
- 532 Perry, R.H., Green, D.W., 1997. Perry's Chemical Engineers' Handbook, 7th edition. McGraw-Hill, New-
533 York.
- 534 Rejl, J., Linek, V., Moucha, T., Valenz, L., 2009. Methods standardization in the measurement of mass-
535 transfer characteristics in packed absorption columns. Chem. Eng. Res. Des. 87, 695-704.
- 536 Revah, S., Morgan-Sagastume, J.M., 2005. Methods of odor and VOC control. Biotechnology for Odor
537 and Air Pollution Control. Springer, New-York.
- 538 Roustan, M., 2003. Transferts Gaz-Liquide dans les Procédés de Traitement des Eaux et des Effluents
539 Gazeux. Lavoisier, Paris.
- 540 Ruddy, E.N., Carroll, L.A., 1993. Select the best VOC control strategy. Chem.Eng. Prog. 89, 28-35.
- 541 Sanchez, C., Couvert, A., Laplanche, A., Renner, C., 2007a. Hydrodynamic and mass transfer in a new
542 co-current two-phase flow gas-liquid contactor. Chem. Eng. J. 131, 49-58.
- 543 Sanchez, C., Couvert, A., Laplanche, A., Renner, C., 2007b. New compact scrubber for odour removal
544 in wastewater treatment plants. Wat. Sci. Technol. 54, 45-52.
- 545 Sanchez, C., Couvert, A., Renner, C., 2007c. Device for treating a gaseous effluent loaded with
546 odorant compounds using a three-dimensional mesh, corresponding installation and process, Patent
547 WO 2007063104 A1. OTV, France.
- 548 Sander, R., 1999. Compilation of Henry's law constants for inorganic and organic species of potential
549 importance in environmental chemistry, Henry's Law Constants. Max-Planck Institute of Chemistry,
550 Air Chemistry Department Mainz, Germany,
551 <http://enviromap.utah.gov/businesses/E/EnSolutions/depleteduranium/performassess/compliancer>
552 [eport/docs/2014/07Jul/supinfo/appreferences/Sander1999.pdf](http://enviromap.utah.gov/businesses/E/EnSolutions/depleteduranium/performassess/compliancer), access date : december 2016.
- 553 Schlegelmilch, M., Streese, J., Stegmann, R., 2005. Odour management and treatment technologies:
554 an overview. Waste Manage. 25, 928-939.

- 555 Tokumura, M., Nakajima, R., Znad, H.T., Kawase, Y., 2008. Chemical absorption process for
556 degradation of VOC gas using heterogeneous gas-liquid photocatalytic oxidation: Toluene
557 degradation by photo-Fenton reaction. *Chemosphere* 73, 768-775.
- 558 Tokumura, M., Wada, Y., Usami, Y., Yamaki, T., Mizukoshi, A., Noguchi, M., Yanagisawa, Y., 2012.
559 Method of removal of volatile organic compounds by using wet scrubber coupled with photo-Fenton
560 reaction—Preventing emission of by-products. *Chemosphere* 89, 1238-1242.
- 561 Vilmain, J.-B., Courousse, V., Biard, P.-F., Azizi, M., Couvert, A., 2014. Kinetic study of hydrogen
562 sulfide absorption in aqueous chlorine solution. *Chem. Eng. Res. Des.* 92, 191-204.