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Physical absorption of volatile organic compounds by spraying emulsion in a spray tower: Experiments and modelling

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ABSTRACT

This study outlines a volatile organic compounds (VOCs) removal spray tower consisting of an empty cylindrical vessel and nozzles spraying an oil/water emulsion into the vessel. Spraying an emulsion into a spray tower absorbs both lipophilic and hydrophilic compounds, facilitates oil transport, improves the interfacial area (oil coats water droplets) and increases the turbulent flow regime enhancing mass transfer. Toluene was chosen as the synthetic lipophilic pollutant. The choice of the organic absorbent, silicone oil (47v350 Rhordorsil®), was made by considering several properties: thermal and mechanical stability, non-biodegradable nature, insolubility in water and low value of Henry's constant. Gas–liquid mass transfer and the hydrodynamics of the gas–liquid contactor were thoroughly investigated. It was observed that emulsion spraying allowed the dual absorption of hydro- and lipophylic VOCs (efficiency around 90% for both) and strongly enhanced the liquid mass transfer coefficient. Finally, a model describing the efficiency of the process as a function of time was developed. The predicted values are in good agreement with the experimental results.

1. Introduction

Volatile organic compounds (VOCs) are defined as any organic component with saturation pressure greater than 10 Pa at ordinary conditions (Council Directive 1999/13/EC, 1999). This property results in a low boiling point, which causes large numbers of these molecules to evaporate and contribute to climate change, making VOCs the most common pollutants emitted by the chemical process industries, and precursors of ground-level ozone, a major component in the formation of smog.

The presence of VOCs in industrial gaseous effluents, such as wastewater treatment processes, painting and coating processes, petrochemical processes, etc., generates unpleasant odours and is often a source of complaints. Its influence on human health can be critical, especially in industry, where, for example, people who have been exposed to benzene have developed cancer. VOCs can be foul-smelling, carcinogenic, teratogenic or mutagenic (Hueper et al., 1962; Somers, 2011; Sram et al., 2007). In addition to irritability of the mucous membranes, skin and eyes, other risks affecting the central nervous system are commonly associated with VOCs. As a

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Nomenclature

m	Henry's constant in dimensionless form [–]
x	fraction molar of the VOC in the gas phase [–]
y	fraction molar of the VOC in the liquid phase [–]
$[VOC]_{eq}$	VOC concentration when in the equilibrium [ppm]
V_{Mair}	molar volume of air [L mol^{-1}]
V_{air}	volume of air in the balloon [L]
$[COV]_{before\,eq}$	VOC concentration initial before addition of liquid absorbent [ppm]
$V_{Mliquide}$	molar volume of the liquid absorbent [L mol^{-1}]
V_{liquid}	Volume of liquid added into the balloon [L]
He	Henry constant [Pa]
P	total Pressure [Pa]
T	temperature [°C]
a_{total}	total superficial area [m^2 m^{-3}]
α	overlap rate [–]
$E_{G,water}$	efficiency of the spray tower working only with water [–]
$E_{G,emulsion}$	efficiency of the spray tower working with water/oil emulsion [–]
a^o	effective superficial area [m^2 m^{-3}]
φ	molar solute transfer flux [mol m^{-2} s^{-1}]
$D_{A,G}$	diffusion coefficient of a solute A in gas phase [m^2 s^{-1}]
δ_G	of liquid film [m]
R	ideal gas constant = 8.314 [J mol^{-1} K^{-1}]
T_K	temperature [K]
p_i	partial pressure on VOC at gas phase at the interface [Pa]
p	partial pressure of VOC ate gas phase [Pa]
k_G	material transfer coefficient at gas film [m s^{-1}]
k_L	material transfer coefficient at liquid film [m s^{-1}]
C_G	solute concentration in gas phase [mol m^{-3}]
$C_{G,i}$	solute concentration at the interface of gas phase [mol m^{-3}]
C_L	solute concentration in liquid phase [mol m^{-3}]
$C_{L,i}$	solute concentration at the interface of liquid phase [mol m^{-3}]
K_G^o	global material transfer coefficient [kmol m^2 s^{-1}]
k_G^o	material transfer coefficient at gas film [kmol m^2 s^{-1}]
k_L^o	material transfer coefficient at liquid film [kmol m^2 s^{-1}]
$Sh_G = \frac{k_G . d_g}{D_{A,G}}$	Sherwood number at gas phase [–]
$Sc_G = \mu_G / D_{A,G} . \rho_G$	Schmidt number at gas phase [–]
$Reg = U_g . d_g . \rho_G / \mu_G$	Reynolds number in the drops
d_g	drop's diameter [m]
Z	tower height [m]
HTU_{OG}	height of transfer unit in gas fluid [–]
NTU_{OG}	number of transfer unit in gas fluid [–]
G	molar Gas flow [mol s^{-1}]
L	molar Liquid flow [mol s^{-1}]
Ω	transversal area of the tower [m^2]
A^*	absorption rate defined by $A^* = L/mG$ [–]
E_G	absorption efficiency calculated by the gas in and out let of the tower [–]
μ	viscosity [Pa s]
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
U_E	drops effective velocity [m s^{-1}]
U_g	drops terminal velocity [m s^{-1}]
$We = U_b . \mu_L / \sigma_L$	Weber number for the drops [–]

consequence of those risks, limit values have been set by the World Health Organization, restricting the concentration of such components to which people can be exposed and, in late 2013, the International Agency for Research on Cancer assessed the carcinogenicity of outdoor air pollution (Loomis et al., 2013). Consequently, rules concerning industrial gas emissions are becoming increasingly strict.

To reduce VOC concentration in air, the first action that needs to be taken is to reduce the production of VOCs at the source by optimizing processes and reducing the use of solvents. Unfortunately those actions are not sufficient or cannot be applied in all chemical processes. In these cases, a specific treatment must be used for the reduction, with the goal of recovering or eliminating VOCs. Noteworthy among eliminative treatments are thermal processes, with or without a catalyst, and biochemical methods, many of which are still in the research or development phases with new and innovating technologies. The choice of the abatement method depends on the temperature, composition and concentration of VOCs in the pollution; the gas flow rate; and the installation and running costs.

The most common ways of treating VOC pollutants in air by a recovery process are condensation, absorption, adsorption and membrane separation (Khan and Ghoshal, 2000).

The technology most widely used for the recovery of VOCs is adsorption, usually with activated carbon, although other adsorbents such as zeolites can be used. This is essentially a batch process since the capacity of the adsorbent is limited. Regeneration of the adsorbent is usually obtained by either heating the adsorbent or stripping with steam (Hester and Harrison, 1995).

Further recovery techniques include absorption and condensation. Absorption involves the transfer of a soluble gas molecule to a solvent liquid, such as water or low volatility hydrocarbons. Absorption systems can treat waste gases containing very high concentrations of VOCs (ranges from 500 to 5000 ppm). Condensation also works well at high VOC concentrations but the technique is most applicable for organic pollutants having reasonably high boiling points relative to ambient conditions.

Classically, absorption is used to remove VOCs from gas streams by bringing the contaminated air into contact with a liquid solvent. Any soluble VOCs transfer to the liquid phase and the air stream is effectively scrubbed. This takes place in an absorber tower designed to provide the gas–liquid contact area necessary to facilitate mass transfer. Using tower packing and trays as well as liquid atomization can provide this contact (Roustan, 2003). Packed bed scrubbing uses packing material to improve vapour–liquid contact. Packing can either be randomly dumped or stacked in the tower. Packing varies widely in size, cost, contact surface area, pressure and material of construction and each packing design has its own advantages (Kherbeche et al., 2013). The packing increases the contact surface area between the phases, and reduces the height needed for the tower (Bhatia et al., 2004). On the other hand, the pressure drop and the energy needs are much greater than in