Purification of air from volatile organic compounds by countercurrent liquid gas mass transfer absorption process

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ABSTRACT

Nowadays environmental sustainability is a fundamental requirement for the development of any process. In this regard, European Union applied directives on emission reduction commitments. In such circumstances, it is mandatory for industries or facilities to adopt proper pollution control measures to meet the requirements.

The absorption process can be a simple, safe, regenerative and recovery technique, selective for the species. The aim of this work is to study the purification process of polluted air containing volatile organic compounds by absorption towers. The evaluation of the feasibility of the process and the effects of operative conditions on the efficiency will be discussed.

Ethyl acetate was selected as a representative volatile organic compound chemical model. We experimentally purified air containing this pollutant at different concentrations by absorption with pure water, changing the temperature and the ratio between water and air flowrate. We investigated the effect of different packagings and their height using two columns: the first one with Sulzer rings and the second one with Raschig structured packaging. Finally, the effect of recycled solvent in the absorption process was considered.

PRO/II software simulator enabled a steady-state simulation of the tests obtaining an excellent fitting of the experimental data.

Introduction

Air quality is an important factor affecting the welfare, health and climate of our planet. The air pollution is a complex problem, as human emissions come from many sources.

Volatile organic compounds (VOCs) are one of the main class of pollutants. They include all the organic compounds with a vapour pressure equal or higher than 0.01 kPa at 20 °C (Directive 1999/13/EC). Due to their high vapour pressure and low boiling point, these substances easily evaporate into the air. VOCs are composed mainly of carbon, hydrogen, oxygen, nitrogen, sulphur or halogens [17]. In general, the most common molecules are BTXS (benzene, toluene, xylenes and styrene), terpenes, formaldehyde and acetaldehyde [25], but the air contamination by different VOCs can be very different depending on the specific industry, geographical area and indoor or outdoor conditions [15].

Depending on the specific molecule, VOCs can cause a wide range of effects from sensory discomfort to damage to numerous organs or systems. Some of them, as for example benzene, formaldehyde, acetaldehyde and naphthalene, are carcinogens [9].

For these reasons, the VOCs removal from air is a very important issue. The European Union has adopted some directives (Directive 2010/75/EU 2010 on industrial emissions and directive 2004/42/CE on the limitation of emissions of VOCs due to the use of organic solvents) to regulate and reduce the VOCs emissions.

Depending on the type of source, VOCs can be anthropogenic (coming from biological decomposition of vegetables, geothermal activities in fossil deposits and combustion processes) or biogenic (petrochemical industry, production of rubbers and polymers, paints, pesticides, disinfectants). They are present in numerous industrial processes. Moreover, they are also one of the main sources of indoor pollution coming from varnishes, waxes, solvents, detergents, or cleaning products present in the buildings. Consequently, a purification system can be useful and applicable in different areas [5].

There are many techniques available to control VOCs emission with many advantages and limitations: catalytic or photocatalytic oxidation [4], adsorption [28], bio-filtration [23], condensation, absorption [13]. The choice of one technique over another depends especially on the nature and concentration of the VOCs species, but also on the gas flow rate to purify, the process safety, the dimension limitations, the need to recover them and the cost of the process.

Absorption process can be considered as generally cheap, safe and regenerative for several potential applications, in particular when sim-

ple water can be used as solvent media thank to the advantageous Henry coefficient respect the contaminant to remove from air. Moreover, it is a recovery technique, i.e. VOCs can be recovered in a second step of the process. It involves the transfer of one or more species (solute) from a gas phase to a liquid phase (solvent or absorbent), which is selective for this species. It allows to handle a wide range of concentrations and to reach a good efficiency.

Gas absorption is useful in separation of gas mixtures, removes impurities, and can recover valuable chemicals. The driving force may be physical or chemical, the former when only physical interactions are present and the latter in the case a chemical reaction is involved. The optimization of this kind of unit operations needs to consider simultaneously the fluid-phase equilibria present in the chemical system and the physical mechanisms involved in the unit, as described for example by Izadi et al. for solid-liquid separators [14].

The process occurs in an absorption column, which has the function to put in contact the two phases and enlarge the contact area between the solvent and the polluted air, increasing the purification rate. In order to obtain a higher efficiency, the column body is loaded with a random or structured packing, which is composed of inert material with specific characteristics (large surface area per unit of volume, large free section for the passage of gases, low specific weight, good mechanical strength, corrosion resistance and low cost). The structured packing is more expensive but it allows to reach the highest contact area between the two phases and assures lower pressure drops. Detailed computational fluid dynamics investigations can be proposed to optimize the complex transport phenomena involved in these processes [20].

Another important factor in the absorption process efficiency is the choice of the absorbent. It depends on the type of impurity. An ideal absorbent should have a high absorption capacity, low vapour pressure to reduce its losses, low viscosity and has to absorb selectively the impurity. It should be non-corrosive, non-toxic, non-flammable, economical, chemically and thermally stable. When the impurities is hydrophilic, water is an efficient absorbent; in the case of hydrophobic species, organic liquids or emulsions with water are better solutions.

Ionic liquids are good absorbents for more hydrophobic VOCs, they easily absorb toluene, dimethyl sulfide (DMS), dimethyl disulfide (DMDS) and dichloromethane (DCM). These absorbents are expensive, but give a good absorption efficiency and can be desorbed and recycled at low temperature [17].

Biard et al. studied the possibility of using heavy solvents in the absorption process, these substances are less selective than water but applicable for a large panel of VOC. PDMS 50 and DEHA purified toluene with an efficiency higher than 90%, but they were less effective for some VOCs such as isopropanol, acetone and DCM (3 m column, at atmospheric pressure and $L/G = 2$) [1].

Another possibility is to use an emulsion to absorb both hydrophobic and hydrophilic VOCs, Dumont et al. employed a water/silicon oil emulsion to purify polluted air containing DMS, DMDS and toluene. They concluded that for VOCs having high affinity for silicon oil, the use of an emulsion respect to pure silicon oil increases the operating costs [7].

A cheaper and environmentally friendly alternative method is the use of vegetable oil in a water/oil emulsion. Sunflower oil allowed to have not VOCs release from the oil and due to its thermal stability, it enabled the thermal regeneration, having a lower oil consumption [11].

Nevertheless, water remains the greenest and cheapest solvent by definition and its use can be optimized with different columns configuration. Moreover, the recovery of VOCs from water exiting from the column can be easier respect the same operation on other, more complex, solvents. Several new technologies are under development for the use of water as working fluid [19].

The aim of the present work was to study the feasibility of the polluted air purification process by absorption towers using pure water as absorbent. Ethyl acetate has a high vapour pressure that allows to have a measurable concentration in the polluted air stream and it is hydrophobic enough to see the effects of the absorption parameters on the process

efficiency. Considering these characteristics, we chose ethyl acetate as VOCs model and we performed the absorption experiments in a countercurrent bench-scale packed column at different operative conditions. Ethyl acetate is a particular volatile organic compound due to its partial affinity respect water. It results in fact less soluble in water respect other VOCs, as acetone for example, and more soluble respect others, as toluene or benzene. This behaviour is explained on the basis of its Henry coefficient (H=8.01, 2.13, 344 for ethyl acetate, acetone and toluene respectively [10]). Then, it be may considered as a good chemical model to evaluate its potential removal from air by water absorption process to represent hydrocarbon with limited affinity towards water. The system water-ethyl acetate is highly not ideal, in fact its liquid vapour equilibria is characterized by azeotropic composition [12]. In recent review papers that analysed absorption technology, ethyl acetate was not considered; Biard et al. evaluated the possibility to use simple water for VOCs absorption using as chemical model toluene, dichloromethane, propanol and acetone [2]. Patel et al. analysed the removal of 48 volatile organic compounds by absorption but ethyl acetate was not considered [21]. Summarizing, the aim of the present paper is to study, using both experimental and simulation approaches, the absorption of a VOC with partial and not ideal affinity towards water. Moreover the effect of several operative parameters will be analysed and discussed.

The type of column packing, the temperature, the L/G ratio (ratio between the flowrate of the gas to purify and the flowrate of the washing solvent), the recycle of the solvent and the column height are the factors affecting the absorption efficiency.

We replicated and compared the experimental tests with the use of a software simulator PRO/II by Aveva Company, after the validation of the thermodynamic method used to represent the fluid phase equilibria involved in the system air–water–ethyl acetate.

Materials and methods

Experimental set-up

We investigated the purification of air containing ethyl acetate by absorption in pure water using two packed columns, 1 m height [3]. The only difference between the two columns was the type of packing: one with random packing (Raschig rings) and the other with structured packing, produced by Sulzer. The Rashig rings are hollow ceramic cylinders (60×60 mm) loaded randomly in the column, the structured packing has a complex wavy structure made of stainless steel (DX type) [3]. The experimental setup of the two columns is identical and it is shown in Fig. 1. The columns are vertical glass tubes with internal diameter equal to 0.043 m, the random packing (Rashig) height is 0.90 m and the structured one (Sulzer) is 0.39 m. Sulzer bodies, DX type, were designed to work for this diameter of the column with negligible wall effects, while the ratio between the diameter of Rashig rings and the diameter of the column can be considered as suitable to avoid significant wall effects [18].

We indicated the bottom of the column with the number 1 and the top of the column with the number 2. All the molar fractions reported in this paper are referred to ethyl acetate. All the parameters in the calculations are defined below:

G, L: gas and liquid flow rates in moles per unit of time and section ($\frac{mol_{tot}}{h\,m^2}$)

G_S, L_S: gas and liquid inert flow rates, that is pure gas or liquid solvent ($\frac{mol_{inert}}{h\,m^2}$)

$$y = \frac{moles\ of\ impurity\ in\ the\ gas}{total\ moles\ in\ the\ gas} \quad Y = \frac{moles\ of\ impurity\ in\ the\ gas}{moles\ of\ inert\ in\ the\ gas}$$
(1)

$$x = \frac{moles\ of\ impurity\ in\ the\ liquid}{total\ moles\ in\ the\ liquid} \quad X = \frac{moles\ of\ impurity\ in\ the\ liquid}{moles\ of\ inert\ in\ the\ liquid}$$
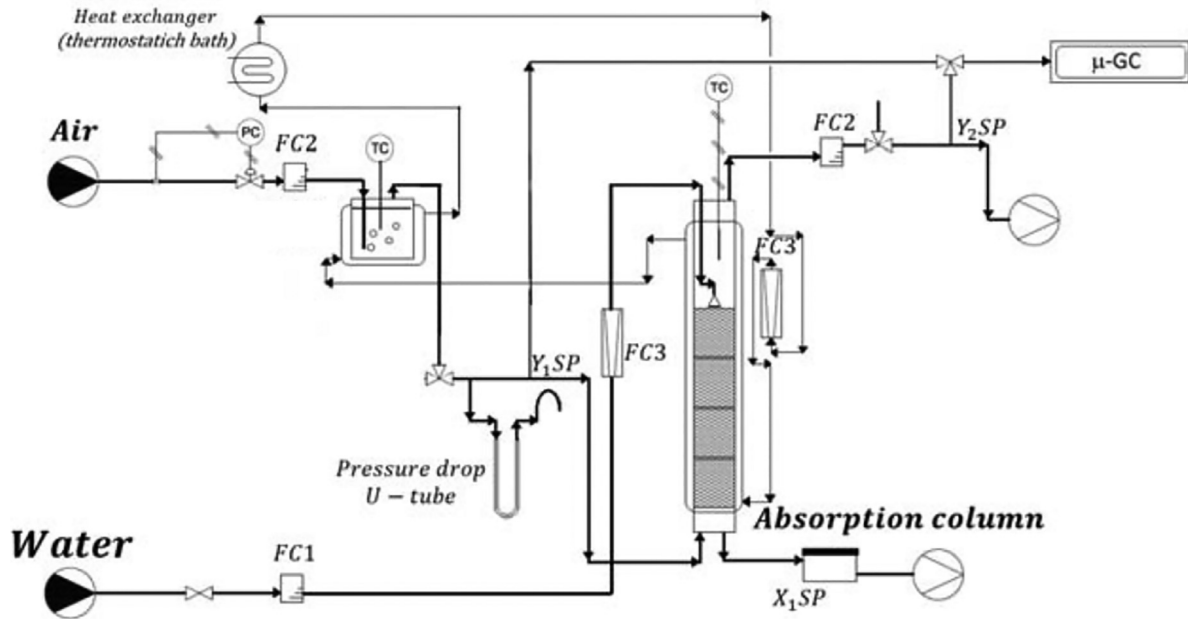(2)

Fig. 1. Absorption column experimental set-up. PC= Pressure Control; FC= Flow Control; SP= Sampling Point; TC= Temperature Control.

In the plant, compressed air passes through a pressure reducer and in a mass flow to regulate the flow. It enters inside a tank containing ethyl acetate in liquid phase. The tank has a cooling jacket connected to a thermostatic bath to keep the temperature constant. The concentration of ethyl acetate inside the gaseous flow is proportional to the temperature of the liquid ethyl acetate, because changing the temperature also the vapour pressure of the substance changes and consequently the air composition. The columns work counter-current: the flow of polluted air (G_1 with composition y_1) enters from the bottom of the column, passes through the packing inside the column entering in contact with the absorbent and exits from the top of the column with composition y_2.

The water passes through an ion-exchange resin beds to deionize, then in a rotameter and a magnetic flow meter to fix and measure the flow. It enters from the top of the column (L_2) and absorbs the impurity, exiting from the bottom of the column with composition equal to x_1. Outside the column in the water line there is a point for sampling. The solvent is always pure water, so the initial composition x_2 is equal to zero.

The column has a cooling jacket in order to keep the temperature constant, in fact this is one of the parameters that affects the absorption process efficiency. A thermometer inside the tank with the liquid ethyl acetate and a thermocouple in the column record the temperatures. A U-tube filled with silicon oil measures the pressure drop between the bottom of the column and the atmospheric pressure.

A Micro-GC 490 produced by Agilent Technologies, equipped with chromatographic column type M5SU (molecular sieve) at temperature equal to 160 °C analysed the entering and exiting air. A UV spectrophotometer analysed the exiting water containing ethyl acetate.

We investigated the temperature effect repeating the same tests changing the temperature of the column from 14 °C to 20 °C. The L/G ratio is the ratio between the flowrate of the washing water (L in L/h) and the flowrate of the polluted air (G in Nl/h). We tested two different values of L/G: 0.008 and 0.01. The values of water flowrate were fixed starting from about 20% above the wettability limit of the filling bodies. Another important parameter is the type of packing: the same experiments occurred with Raschig rings and Sulzer structured packing.

A different experimental configuration was used in order to investigate the effect of different column height on the efficiency. For this study, we connected the two columns in series. In this set up the water enters from the top of the Raschig column and flows inside the two

columns exiting from the bottom of the Sulzer column. The polluted air enters from the bottom of the Sulzer column and flows through the two columns reaching the top of the Raschig column. The system allows to analyse not only the composition of entering gas (y_1) and exiting gas (y_2), but also the composition of the gas between the two column by μ-GC analysis (y_{int}).

Finally, to evaluate the feasibility of recycling back the water, we added a pump connected to a closed tank (volume= 2 L) on the bottom of the columns in series. The pump recycled the water exiting from the bottom of the Sulzer column back to the Raschig column. During the test the flow of ethyl acetate was continuous and constant in concentration. Two liters of water initially pure ($x_2=0$ at $t=0$) were recycled at 4.5 L/h for 195 min. Considering the time zero when the pump started to work, we measured the concentration of pollutant in the exiting gas (y_2) every 3 min.

Pressure drops were measured for all the experimental test, and they resulted very low for both the columns. For example, at 17 °C with 1,9 Nl/h of air and 1.4 L/h of water the pressure drop for Sulzer and Rashig columns were 340 Pa/m and 730 Pa/m, respectively.

Results and discussion

To quantify the performance of the column for air purification, the column efficiency was calculated with the following equation.

$$Column\ efficiency\ \% = \frac{\left(\frac{mol\ ethyl\ acetate}{h}\right)_1 - \left(\frac{mol\ ethyl\ acetate}{h}\right)_2}{\left(\frac{mol\ ethyl\ acetate}{h}\right)_1} * 100 \quad (3)$$

that is

$$Column\ efficiency\ \% = \frac{G_s Y_1 - G_s Y_2}{G_s Y_1} * 100 = \frac{Y_1 - Y_2}{Y_1} * 100 \quad (4)$$

The VOCs removal efficiency obtained using different filling bodies for different operative conditions are compared in Table 1. Considering that the Sulzer packing (0.39 m) is shorter than the Raschig packing (0.90 m), the structured packing has a higher efficiency for unit of length.

Theoretically increasing the L/G ratio the efficiency of the process increases [6]. The experimental tests showed that both the Raschig and Sulzer columns correctly follow this trend, as results from Fig. 2.

Table 1
Comparison of column efficiency using different filling bodies.

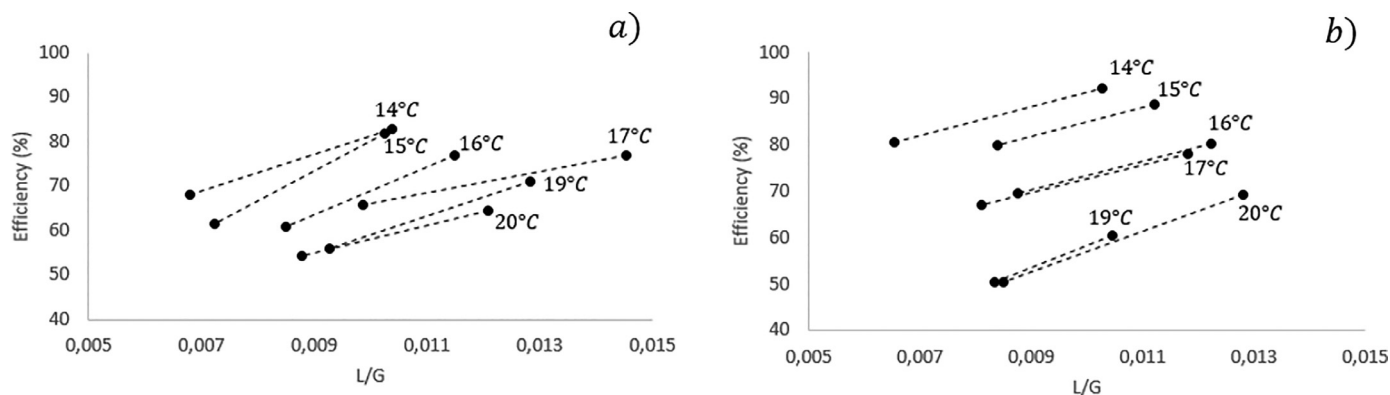| Air flowrate (Nl/h)	Water flowrate (L/h)	y_1	T column (°C)	Efficiency Sulzer (%)	Efficiency Raschig (%)
152	1.2	0.10	17	66	65
152	1.6	0.10	17	75	73
173	1.6	0.06	18	68	68

Fig. 2. Effect of L/G variation for different column temperatures for a) Sulzer column and b) Raschig column.
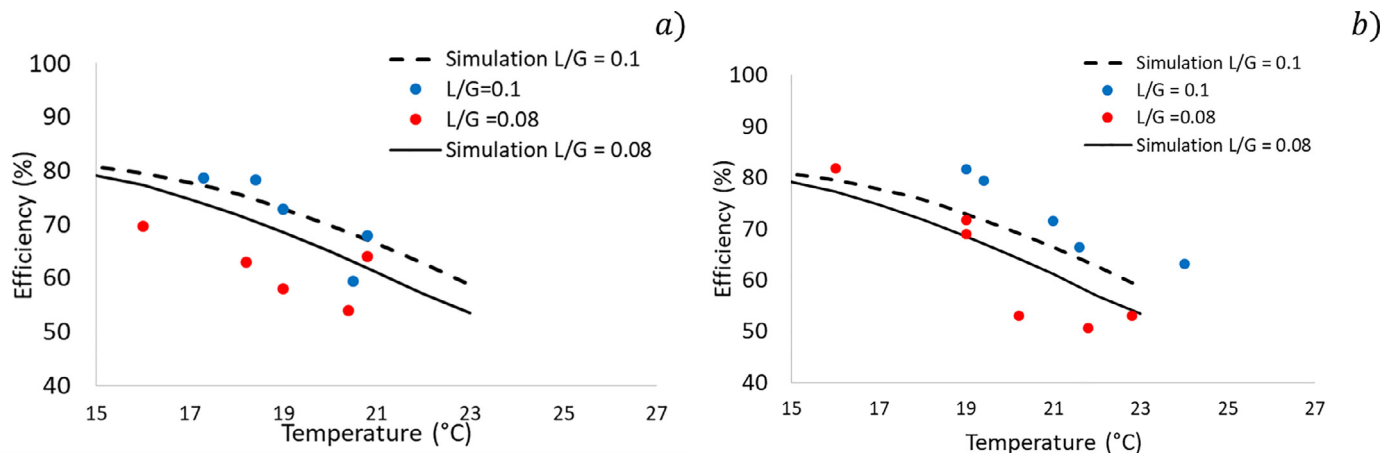

Fig. 3. Temperature effect for a) Sulzer column and b) Raschig column.

For each column temperature, we reported two L/G values: in all the tests increasing L/G, the efficiency increases. Even at very low L/G ratio (between 0.006 and 0.009), depending on the temperature, the system reached high efficiencies: the highest value was 92% at 14°C and L/G=0.01 (Raschig column), the lowest was 50% at 20 °C and L/G=0.008 (Raschig column).

Temperature effects the vapour pressure of the components, diffusion coefficients, gas density and viscosity [16]. The influence of this parameter on the absorption process is shown in Fig. 3a, where the efficiencies of Raschig column operating at L/G = 0.1 and 0.08 were reported. The same data are reported for Sulzer column at L/G = 0.1 and 0.08 in Fig. 3b. The data are scattered because of the different experimental uncertainties regarding the measures. A K-type thermocouple at the top of the bed, with a precision of 0.1 °C, measures the temperature of the column. It was not possible to measure the temperature of the column in other points inside the packing and there is the possibility that the recorded value of temperature were not very precise. In fact, at the top of the column where the thermocouple is, the washing water enters at higher temperature respect to the column temperature.

However, the observed trend is in accordance with the expected values: the higher the temperature, the lower the efficiency for both the columns.

Table 2
Effect of Sulzer and Rashig bed height.

	Columns in series	Sulzer	Raschig
y_1	0.072	0.064	0.072
y_{INT}	0.22	–	–
y_2	0.010	0.021	0.025
L/G	0.0084	0.00790	0.0076
Efficiency (%)	87	68	68

The height of the Rashig and Sulzer bed is another parameter that influences the efficiency of the process. In order to understand how the column height effects the absorption process we repeated the same test using the two columns in series. The results are reported in Table 2 by comparing the efficiency of ethyl acetate removal by using single columns (Rashig or Sulzer) and the same columns connected in series.

Increasing the height of the column the efficiency increases, this is due to the increasing of contact area between liquid and gas phases. The efficiency is not equal to the sum of the two columns efficiencies, in fact when the system is closer to the equilibrium the driving force of the process decreases and more equilibrium stages are necessary to purify the polluted air.
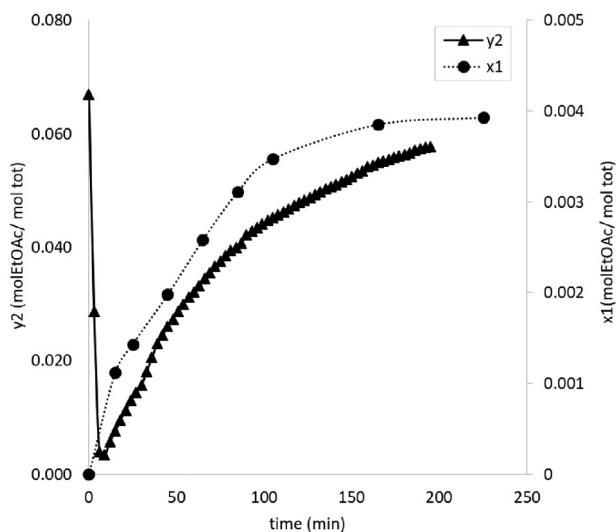
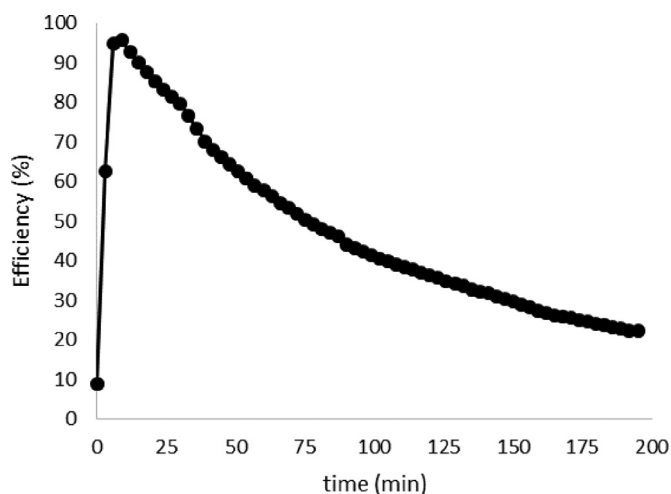**Fig. 4.** Recycle of water using two columns in series ($y_1 = 0.073$, T column=27.0 °C, $L/G = 0.0256$).

Fig. 5. Efficiency with recycle of water using two columns in series ($y_1 = 0.073$, T column=27.0 °C, $L/G = 0.0256$).

Effect of solvent recycle

Using the double columns configuration explained before, we observed how the efficiency of the process changes recycling the solvent. The polluted air continuously flowed through the two columns with initial molar fraction equal to 0.073 (y_1) for 195 min. When the liquid pump started, the water was pure and almost completely purified the polluted gas flow (y_2 line), as it results in Fig. 4 for time near to zero. During the time, water (x_1 line) absorbed ethyl acetate starting to purify less and less.

Fig. 5 shows how the efficiency changes during the time of the test, initially the efficiency increased, at a certain point it started to decrease due to the absorption of ethyl acetate in the water. At the end of the test, the efficiency was equal to 22%.

The results collected with this column configuration show how it is possible to operate with recycling of the washing solvent, in order to use less water. The trends shown in Figs. 4 and 5 depend on the volume of the recycling tank used in the experiments (2 L). With a larger volume, less steep drops in efficiency would have been obtained. The optimization of the recirculation system with the combination with continuous or discontinuous separation processes that would allow to recover ethyl

acetate and at the same time to obtain pure washing solvent will be studied for future works.

Equilibrium and operating curve

At a constant temperature, the amount of a compound in gas phase that dissolves in a given type and volume of liquid is directly proportional to the partial pressure of that gas compounds in equilibrium with the liquid. The Henry's law expresses this equilibrium relationship in case of diluted solution. The proportionality coefficient, under isothermal conditions, is constant and it is called Henry's constant.

$$y = H_{yx}x \tag{5}$$

Considering the relation that binds y and x, referring to Y and X as previously defined, it is possible to write the Henry's equation as:

$$\left(\frac{Y}{Y+1}\right) = H_{yx}\left(\frac{X}{X+1}\right) \tag{6}$$

This equation is the equilibrium curve. Sander et al. reported the Henry's constant for ethyl acetate in different unit of measure and its dependence on temperature [24]. In the following equation is possible to calculate H_{yx} for each temperature.

$$H_{yx} = \frac{1}{H_{cc}}\frac{\rho_l}{MW_l}\frac{MW_g}{\rho_g} \tag{7}$$

where g is for air and l is for water, Hcc is the dimensionless ratio between the aqueous-phase concentration of a species and its gas-phase concentration.

$$H_{cc} = H_{cp} * RT \tag{8}$$

The unit of measure of H_{cp} are ($\frac{mol}{m^3\,Pa}$) and they are expressed as

$$H_{cp}(T) = H°(298.15\,K) * exp\left(\frac{dlnH}{dln\left(\frac{1}{T}\right)} * \left(\frac{1}{T} - \frac{1}{298.15}\right)\right) \tag{9}$$

$H°$ is the Henry's law constant for solubility in water at 298.15 K. The terms $H°$ and the exponential term are tabulated and present in literature [24].

We reported the mole fraction of the impurity in the gas as a function of that in the liquid in equilibrium conditions and operating conditions, obtaining the corresponding equilibrium and operating curves [26]. The operating line is a line passing through the points (X_1, Y_1) and (X_2, Y_2) and its slope is equal to L_s/G_s.

$$\frac{(Y_1 - Y_2)}{(X_1 - X_2)} = \frac{L_S}{G_S} \tag{10}$$

At a certain value of Y_1 (molar fraction of impurity in the gas flow entering the column), the correspondent molar fraction of impurities in the liquid phase exiting the column is X_1. At the equilibrium, it should be equal to the value calculated by Henry's equation X^*.

The difference present between the real value X_1 and the equilibrium value X^* is the driving force of the process: higher is this difference and faster is the process. When L_s/G_s ratio increases, the driving force of the process increases and consequently, the efficiency of the separation increases. The system spontaneously tends to the equilibrium and the further it is, the stronger the driving force will be.

In the absorption process, the operating line is always above the equilibrium curve. Consequently, the experimental value is greater than the equilibrium one and the impurity passes into the liquid phase (Fig. 6).

Process simulations

In order to validate the experimental data we performed a static simulation of the process using the software PRO/II 10.2 by AVEVA Company, using a series of flash units to simulate the column. A flash tank is
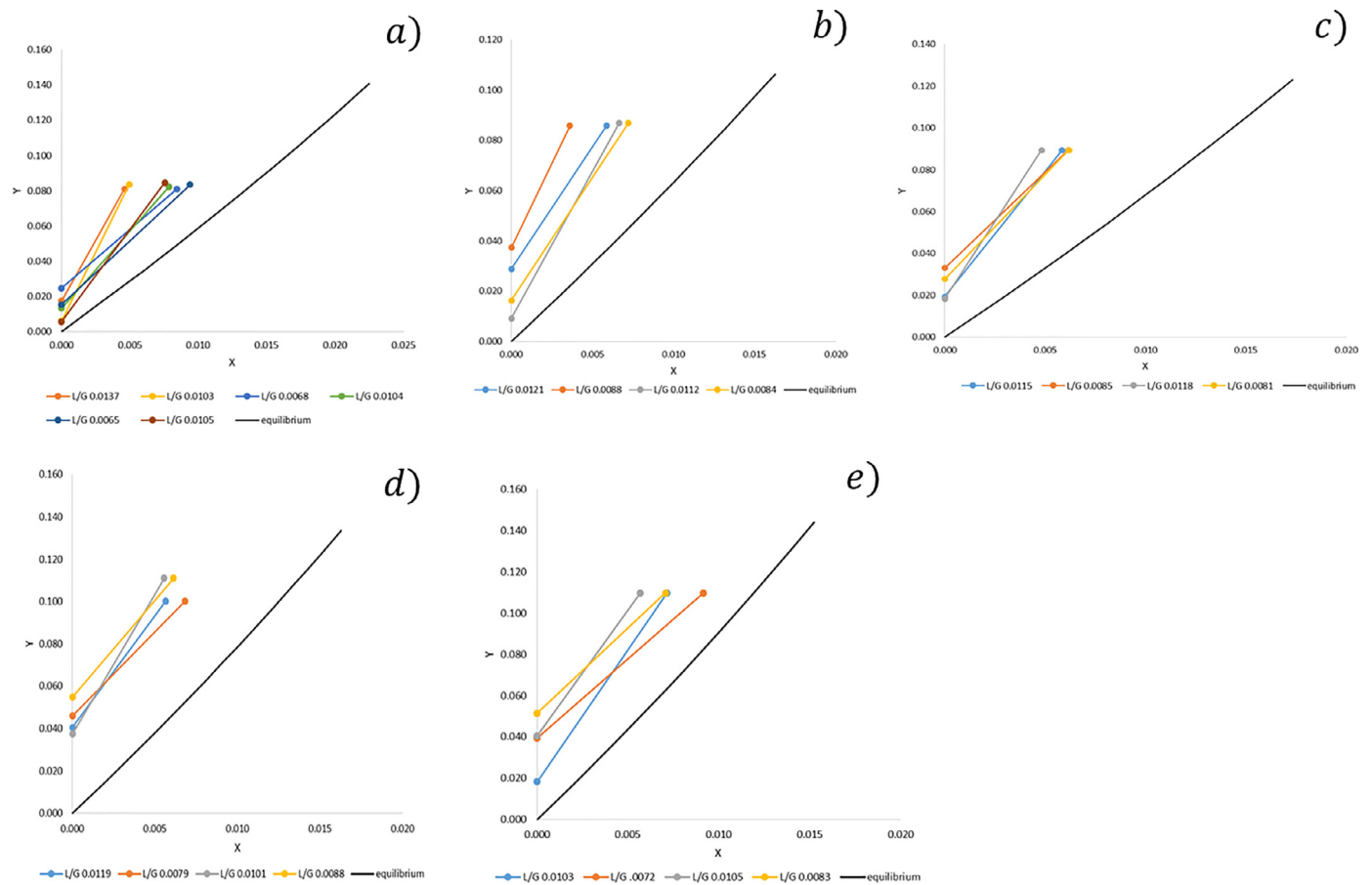
Fig. 6. Equilibrium and exercise curves: a) 14 °C; b) 15 °C; c) 16 °C; d) 19 °C; e) 20 °C.

a single equilibrium stage, able to calculate the thermodynamic equilibrium of a stream (or multiple streams that are mixed inside) according to a temperature and a pressure specification (and a pre-selected thermodynamic model, in this case NRTL). In this way, it is possible to set always the same temperature and connect in series multiple flash tanks to simulate various theoretical stages of the absorption column.

NRTL (non random two liquids) is a thermodynamic model that calculates the activity coefficients of a mixture according to the non random disposition of the molecules (local concentration) in the liquid due to their interaction [27]. It is able to predict liquid–liquid phase separation, however this option was not selected since ethyl acetate is always soluble at the concentrations employed [22]. Each flash tank is a theoretical stage and, according to Caldas and Lacerda, the HETP (Height Equivalent to the Theoretical Plate) of column with small diameter is equal to the column diameter [8].

$$z = (HETP) * (N) \tag{11}$$

$$(HETP) = column\ diameter \tag{12}$$

where Z is the height of the packed bed necessary to obtain a separation equivalent to N theoretical stages. Therefore for the Raschig column with height equal to 0.9 m. N is equal to 20 flash unit. A first flash unit simulates the tank containig the liquid ethyl acetate and it works at the same temperature experimentally measured. The flow exiting this flash has the same composition of G_1 (polluted air entering the column) and enters in twenty flash in series.

In the case of Sulzer column, the company reported 20 as the number of theoretical stages. In Figs. 7 and 8, we reported a comparison between simulated and experimental data. The simulation fits the experimental data for both the columns.
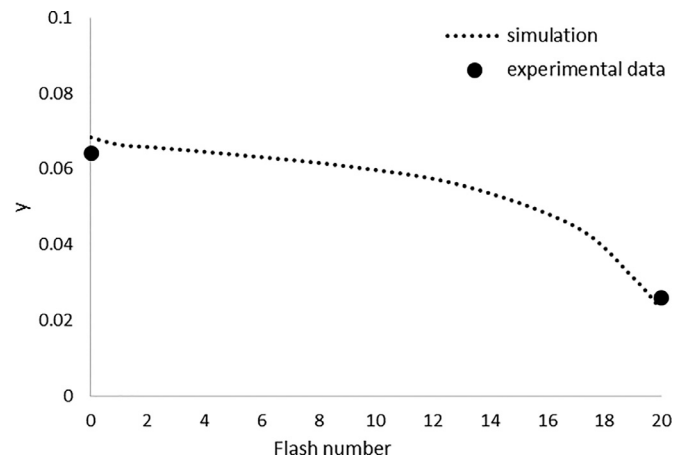

Fig. 7. Comparison simulation and experimental data for Sulzer column (T column=18.0 °C, L/G= 0.0079).

The simulation fits the experimental data for both the columns, as cross validation of the experimental data and the thermodynamic method applied in the calculations.

This study opens up the possibility to evaluate absorption columns with simple water as absorption fluid in several applications, in industrial plants, warehouses, indoor or outdoor places where there is contamination of water-soluble volatile organic compounds. The use of water as absorption solvent can allow this application also in not strictly chemical plant areas. On the other hand, this technology is suitable only
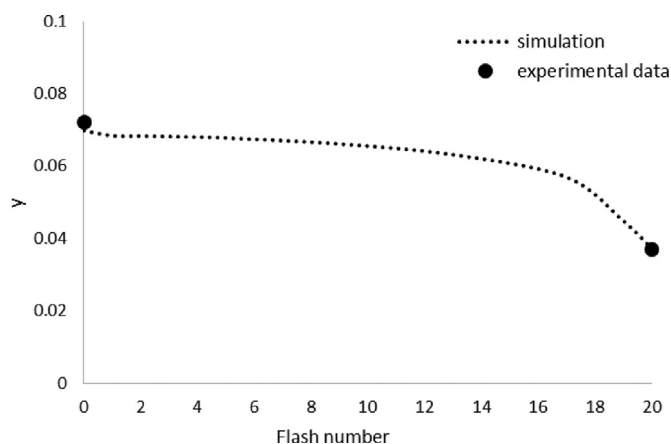
Fig. 8. Comparison simulation and experimental data for Raschig column (T column=18.0 °C, L/G= 0.0056).

if the volatile compounds are characterized by a good affinity with water. Moreover, it must be carefully evaluated in term of water consumption. The possible recover of the VOC and the consequent recycle of water as fresh solvent will considered in future works.

Conclusions

The choice of using ethyl acetate as VOCs model allowed to observe the effect of several operative parameters on absorption efficiency. In particular, we studied the effect of temperature, type of packing, the L/G ratio, column height and solvent recycle. Increasing the temperature of the column the efficiency of the process decreases. The two columns show a very similar efficiency, considering that he Raschig column has a higher packaging height, the efficiency for unit of length for the Sulzer column is higher.

Keeping all the other parameters constant, we investigated the effect of L/G variation. The tests showed that increasing this value the efficiency of the process increases.

We obtain a column with higher height using the two columns in series. The efficiency changed from 67% to 68%, respectively for Raschig and Sulzer column, to 87% for the two columns in series. The efficiency obtained with two columns is not equal to the double of the single column, because the closer the system is to the equilibrium, the lower is the driving force of the system. The operative lines were above the equilibrium curves for all the experimental test, then the operative conditions were distant from the equilibrium.

We investigated the possibility to reuse the water more times recycling it and the process continues to operate, but with decreasing efficiency over time. This result demonstrates the need for correct sizing of the solvent tank under recycling and the development of a continuous or discontinuous method for the separation of water from ethyl acetate.

Absorption process is a suitable method for ethyl acetate separation from air, in fact at room temperature and atmospheric pressure, using even a very low L/G ratio, the system can reach good efficiency for the purification of this compound. Future goals could be to develop a good method for the solvent separation from water, in order to recover it and simultaneously obtain fresh solvent for the absorption column.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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