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Removal of volatile organic compounds from Waste air stream of a furniture factory

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Abstract

In this paper, an alternative to the thermal oxidation of VOC in a gaseous effluent was studied, to lessen power consumption and mitigate the environmental impact of a furniture factory located in the north of Portugal.

A gas–liquid absorption of n-butyl acetate in a packed-bed column of LECA was studied to achieve a VOC outlet in agreement with the Portuguese law for effluent discharge in the atmosphere. Studies of VOC physical absorption with water were evaluated.

Experiments with a continuous flow of tap water demonstrated to be very effective in removing n-butyl acetate of the air stream. Efficiencies over 90% were achieved by this method and in three experiments outlet VOC concentration remained under the imposed limit of 50 mg_C/Nm^3. Other experiments were registered to be above the imposed limit, even so, they were also highly effective, suggesting that if the outlet water can be reused and employed for other purposes, this solution might have an industrial interest. In the other studied approach, with a closed water circuit, the system proved to be less effective, with the removal efficiency of the VOC dropping very fast, which revealed the need for continuous treatment of the recirculated water.

When introducing the microorganisms to the system, the efficiency was lower than for open circuit, averaging, 40.2%, 27.0%, 25.5%, respectively in the three experiments realized, suggesting that the system might be an interesting and a sustainable alternative to the ROT system employed at the factory, with a significant reduction in the energy consumption.

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Keywords: Absorption; Air stream treatment; Biotrickling filter; Volatile organic compounds

1. Introduction

The volatile organic compounds (VOC) introduced into the atmosphere via both biogenic and anthropogenic emissions lead to an increment of the tropospheric ozone, due to the oxidization with NO_X in the lower troposphere, playing an important role in the chemistry of the atmosphere [1].

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VOC are defined as any organic compound as well as the fraction of creosote, having at 293,15 K a vapor pressure of 0,01 kPa or more, or having a corresponding volatility under the particular conditions of use [2].

One important VOC is the n-butyl acetate, a hydrophilic chemical compound, with low volatility, commonly employed as a solvent in industrial processes. Although the discharge of this VOC to the atmospheric air has a negative impact on air quality, it is considered a green solvent due to its low toxicity when compared with other solvents, and its market importance and usability have been increasing over the years [3]. Due to the increasing usage, it is of high importance to mitigate the impact of this solvent in the atmosphere.

The VOC emissions in Portugal are regulated by the *Decreto-Lei 39/2018 de 11 junho* [4], which establishes the regime for the prevention and control of pollutant emissions to air and transposes the European Directive (EU) 2015/2193, of the European Parliament and of the Council, of 25 November 2015, and by the *Decreto-Lei n.º 127/2013 de 30 agosto* [5], which establishes the industrial emissions regime applicable to the integrated prevention and control of pollution, as well as define the rules to prevent and or reduce emissions to air, water and the soil and the production of waste, in order to achieve a high level of protection of the environment as a whole, and transposes the IPPC European Directive 2010/75/EU, of the European Parliament and of the Council, of 24 November 2010 [2]. According to these two legal diplomas, the VOC emissions (expressed in total carbon) for this activity must be lower than the emission limit value of 50 $mg_C/N\ m^3$. According to the Final Draft of the Best Available Techniques Reference Document on Surface Treatment Using Organic Solvents including Preservation of Wood and Wood Products with Chemicals (2019) that is in final phase of approval the BAT-associated emission level (BAT-AEL) for VOC emissions in waste gases from the coating of wooden surfaces for the total VOC is 5–20 mg_C/Nm^3 [6].

Packed bed scrubbing uses packing material to improve vapor–liquid contact. Absorption effectiveness and mass transference kinetics depend on VOC/solvent affinity; diffusivity and equilibrium solubility; density, viscosity, composition and concentration of VOC species in the inlet gas; the desired composition of VOC in outlet air; reactor type; inlet liquid and gas flow rate; temperature and pressure drop [7].

2. Case study

A furniture factory located in the north of Portugal that has a line of solvent-based ink uses a regenerative thermal oxidizer (RTO) to remove VOC from the effluent gas stream.

The RTO process employed at the factory is a common waste gas treatment technology, used for the oxidation of highly contaminated air streams. The purified air is released to the atmosphere, while the energy content of the solvents is used as fuel to maintain the optimal temperature of the chamber at a temperature ranging from approximately 750 °C to 900 °C. However, when the VOC concentration is below the self-sustaining operation inlet concentration, it is necessary to maintain the temperature supplying liquefied petroleum gas (LPG), increasing the costs and reducing the environmental sustainability of the process.

The origin of the pollutant comes from the application of solvent-based inks during the wood surface painting process. The n-butyl acetate represented in 2019, 72% (m/m) of all the consumed VOC at the factory. In order to increase the sustainability of the production process, the company has been replacing solvent-based inks with alternatives with lower VOC content or even with alternative technologies that use UV-cured water-based coatings. This replacement leads to a cleaner gaseous effluent and therefore higher consumption of LPG to compensate for the loss of fuel in the effluent necessary to maintain the oxidation chamber within the optimal operating temperature. The actual characterization of the gaseous effluent from the solvent-based painting line was done punctually in several days and the measured concentration is $224 \pm 165\ mg_C/N\ m^3$ dry gas, which is much lower in concentration than the one indicated to allow the regenerative oxidation process to be self-sustaining: range 700 to 2000 $mg_C/N\ m^3$.

To evaluate the possibility of replacing the treatment technology employed at the plant, a more environmental and economically sustainable alternative to treat at least part of the waste air effluent was studied.

3. Materials and methods

The absorption/biotrickling column consists of a packed absorber tower, composed by a transparent cylindrical plastic acrylic glass column 11.5 cm in diameter and 72 cm in total length. The column was divided into 2 sections, joined by flanges of 1.25 cm each, with a square hole perforated pattern stainless-steel plate located in between the sections to hold the packing. The upper section was 54 cm long and packed with a height of approximately 41 cm

of Light Expanded Clay Aggregate (LECA). It has a high surface area per volume, meaning that microorganisms can adhere and grow in its surface and inside the pores, making them suitable for testing in a biotrickling system. The porous LECA pebbles with an average size of 1.1 cm were used to maximize the contact between the liquid, microorganisms, and the gas phase. The lower section, measuring 15.5 cm, worked as a water reservoir to optimize the dispersion of the gas in the column, providing a total packed bed volume of approximately 3 l.

Bioaugmentation in the biotrickling filter was achieved with lyophilized powder microorganisms, obtained from Biosystems Europe, a granular water-soluble powder composed of saprophytic bacteria and a mixture of phosphate salts and dextrose, designed to use for biological degradation of organic waste material.

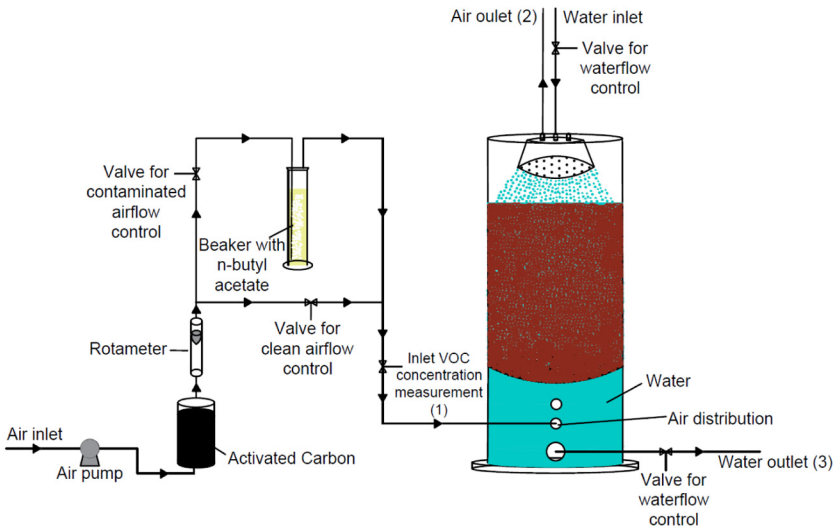

Fig. 1. Representation of the interactions occurring in biotrickling filters.

In Fig. 1 it is presented a schematic diagram of the absorption column in continuous flow, being that it can be adapted to operate in recirculation flow with and without microorganisms. The air VOC concentration was measured at the sections represented in Fig. 1 with the number 1 and 2. The water samples were taken from a tube connected to a faucet at the bottom of the column (3). When operating in closed circuit, the same sampling operations were conducted. All the experiments were conducted until a steady state was achieved.

Total carbon (TC) present in the water was measured by nondispersive infrared sensor (NDIR) and chemiluminescence, using Shimadzu TOC-VCPH/CPN Total Organic Carbon Analyzer and TOC-Control V software.

The VOC concentration of airflow at both inlet and outlet of the column was measured with a Photo-Ionization Detector using a Tiger LT gas detector with 0.1 ppm as minimum resolution.

The industrial effluent characterization at the plant was performed using FID detector Signal according to EN 12619:2013 for VOC. Flow was measured with a Pitot Type S Isostack Basic Tecora according to EN ISO 16911:2013.

4. Results and discussion

4.1. Treatment of waste gas by absorption in water, continuous flow

This study pursuits alternatives to the RTO that is employed at the furniture factory to remove the n-butyl acetate from air by absorption into tap water passing through a packing consisting of LECA, in the system described before. The experiments were done in open circuit by contacting the gas stream in a counter-current flow of water. For this purpose, six different experiments were conducted. The operational conditions of the experiments and results are present in Table 1.

Table 1 shows that all the experiments proved to be effective in reducing the inlet VOC, although only experiment E1, E2 and E6 were effective in reducing VOC concentration to the legal limit of 50 $mg_C/N\ m^3$. In these experiments, different entry concentrations were tested in the range of concentrations indicated to allow the regenerative oxidation

Table 1. Operational conditions of the experiments: average VOC inlet and outlet concentration in the air stream, air and water operation flow and removal efficiency of the process.

Experiment	Inlet Conc. ($mg_C/N\ m^3$)	Outlet Conc. ($mg_C/N\ m^3$)	Air operation flow (Nl/h)	Water operation flow (l/h)	Water outlet Conc. (mg_C/l)	Removal efficiency (%)
E1	1694.7	0.0	255.3	305.0	1.40	100.0%
E2	2411.4	5.2	582.4	332.0	4.07	99.8%
E3	1680.0	74.3	581.2	61.0	15.02	95.6%
E4	3321.1	174.2	582.4	44.0	40.54	94.8%
E5	514.4	78.0	561.5	21.1	11.47	84.8%
E6	514.4	49.2	560.9	36.0	7.10	90.4%

process to be self-sustaining (range 700 to 2000 $mg_C/N\ m^3$). Therefore, it was always used conditions close to or much higher than the maximum concentration observed in the current reality of the factory unit, which was 550 $mg_C/N\ m^3$.

4.2. Treatment of waste gas by absorption in water, closed circuit

Two experiments (CF1 and CF2), with water recirculation averaging 442.1 l/h, in closed circuit, were conducted with different airflow and VOC inlet concentration. In CF1 the VOC concentration was on average 1931.8 $mg_C/N\ m^3$ and for CF2 the VOC concentration was on average 214.7 $mg_C/N\ m^3$.

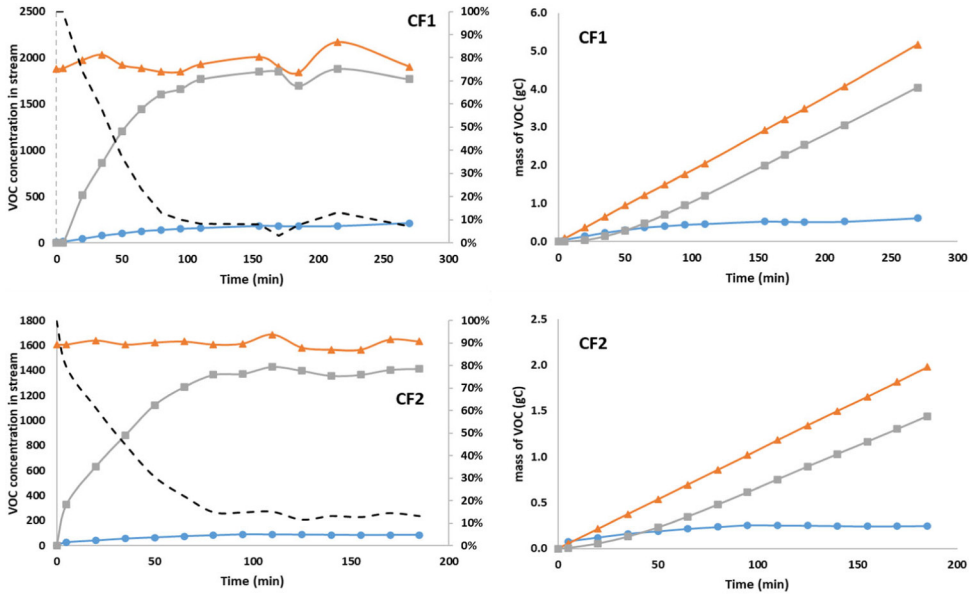

Fig. 2. Process efficiency and concentration ($mg_C/N\ m^3$) of n-butyl acetate in the outlet and inlet airflow and, outlet waterflow in function of time (left) and accumulated carbon mass (g) of n-butyl acetate in the outlet and inlet airflow and, outlet waterflow (right).

From Fig. 2, it can be seen that the concentration limit value is quickly reached. Only with the treatment of the VOC absorbed by the water or a timely opening of the treatment water circuit will make this approach a viable solution.

4.3. Treatment of waste gas by absorption in water, closed circuit with microorganisms

In Table 2 it is possible to address the operational conditions of the biotrickling filter for three different experiments, M1, M2 and M3, in which the water operation flow was on average 442 l/h.

Table 2. Operational conditions of the experiments: average VOC inlet and outlet concentration in the air stream and air operation flow, elimination capacity, removal efficiency of the process mass loading rate, empty bed residence time and elimination capacity.

Experiment	Inlet Conc. ($mg_C/N\ m^3$)	Outlet Conc. ($mg_C/N\ m^3$)	Air operation flow (Nl/h)	Mass loading rate ($g_{VOC}\ m^{-3}\ h^{-1}$)	Empty bed residence time (s)	Removal efficiency (%)	Elimination capacity ($g_{VOC}\ m^{-3}\ h^{-1}$)
M1	1586.4	989.1	238.6	137.68	67.55	40.2	55.08
M2	186.1	145.2	636.5	43.30	24.36	27.0	12.07
M3	170.7	76.8	279.8	14.80	59.37	25.5	13.40

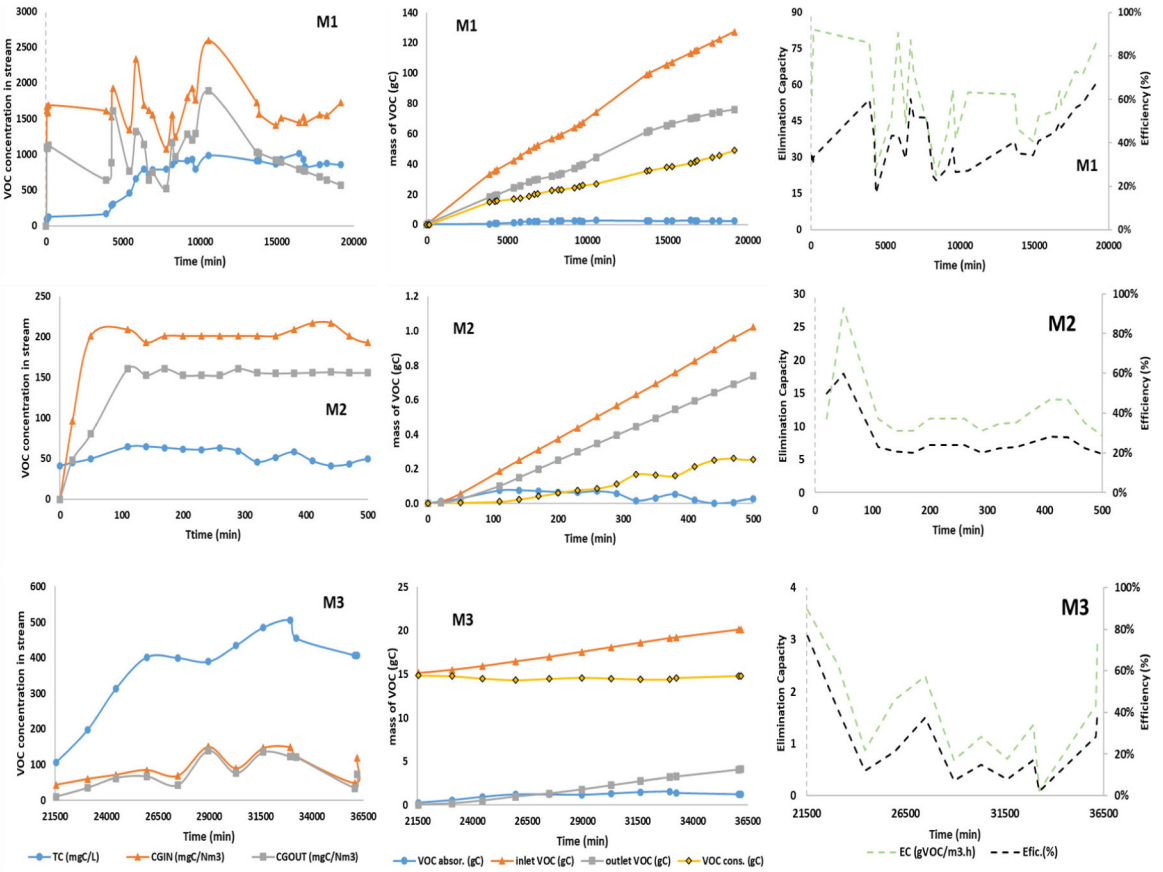

Fig. 3. Process concentration ($mg_C/N\ m^3$) of n-butyl acetate in the outlet and inlet airflow and, TC present in the outlet waterflow in function of time (left) and accumulated carbon mass (g) of n-butyl acetate in the outlet and inlet airflow and, outlet waterflow in function of time (center) and elimination capacity ($g_{VOC}\ m^{-3}\ h^{-1}$) and removal efficiency (%), in function of time (right).

In Fig. 3 is presented a graphical representation of the results given by the three experiments in function of time.

Analyzing Fig. 3, the first and foremost evidence of improvement on the using of microorganisms, when compared without microorganisms, is the time that it was possible to maintain the column operating without saturating the water and drastically reducing efficiency. This is clear in M1 and M2. When compared to CF1 and CF2, it is possible to say that the microorganisms played a key role in keeping the TC in the water down and with low efficiency variability.

Even though the microorganisms were successful at increasing the time on which it is possible to operate, they were not successful at reaching the desired 50 $mg_C/N\ m^3$ target. Two major parameters, empty bed residence time (EBRT) and mass loading rate (MLR), are usually considered regarding the biotrickling process since they are useful to reach the desired outlet concentration [8]. It seems that higher EBRT and lower MLR or a combination of both can improve the results and therefore reaching values lower than the discharge limit.

Another interesting parameter is the elimination capacity (EC) that gives a perspective of the overall VOC consumption performed by the microorganisms. According to the results, EBRT and MLR seem to have an impact on EC performance.

5. Conclusion

It can be concluded that an absorption tower with a pack of LECA, either in continuous flow or recirculation flow, is an effective way of removing n-butyl acetate from the air.

The results indicate that n-butyl acetate has a good affinity with water, reaching removal efficiencies above 90% being reached for a continuous flow of water. These results show that it is possible to reduce the content of different concentrations of VOC totally or partially, for similar gas flows, to the desired concentrations by regulating the water flow. As a final stage of the continuous flow system, the water should undergo a stripping process to be reused.

As expected, the column in recirculation flow reaches a steady-state, but when the water is saturated with n-butyl acetate it is verified a low removal efficiency, confirming this as the less effective method of the three studied, which means that the water should be changed from time to time to maintain high efficiency levels.

When introducing the microorganisms to the system, the efficiency of VOC reduction averaging 40.2%, 27.0%, 25.5%, respectively for the three experiments. These preliminary results allow to conclude that the use of bioaugmentation in biotrickling filters has an interesting potential to reduce the concentration of VOC in the waste gas. Thus, the possibility of the utilization of a more sustainable waste gas treatment technology, in accordance with the tendency of reducing the VOC concentration that could be used at least in the less concentrated air streams, would represent a significant reduction of operational and energy costs and in the environmental impact of the company.

CRediT authorship contribution statement

João R. Silva: Investigation, Data curation, Formal analysis, Validation, Writing - original draft. **Dânia S. Ascensão:** Data curation, In situ measurements. **Luís M. Castro:** Data curation, Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition.

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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