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Abatement of volatile organic compounds from the exhaust gases of an industrial bakery oven: comparative analysis of different technological solutions

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Abstract

Industrial processes can lead to the emission of organic chemical compounds in the environment. These compounds, usually referred to as “volatile organic compounds” (VOCs), are harmful to the environment and contribute to the air pollution of industrialized areas. Indeed, they are classified as particulate matter (PM) and are considered to be ozone precursors. During the last decades, the release of VOCs in the environment has become a major issue, leading to the implementation of specific regulations and to the development of several VOC-abatement systems.

In this study, we focused on the bakery sector, where the VOCs, mainly ethyl alcohol, evaporate during the baking process due to the high temperatures reached in the ovens and are released from the baking chamber. We performed a detailed review of existing and emerging VOC-reducing systems, classified into “combustion” and “non-combustion” control devices, among which we identified five technologies that resulted to be the most suitable for the bakery sector. We carried out technical and economic evaluations for each technology, by interviewing both technology providers and end-users of VOC abatement technologies. Finally, we determined the optimal technology as the one that allowed for reaching the best trade-off among legislative, environmental and economic aspects.

Keywords: bakery, industrial oven, volatile compounds, feasibility study, multi-criteria analysis

1. Introduction and state of the art

The constant increase in human activities has caused, particularly in the last decades, an alteration in the quality of the air. Natural sources, civil structures and industrial plants release every day several air pollutants, which affect both the environment and public health (Atkinson, 2000). Volatile Organic Compounds (VOCs) are particularly harmful to the environment. Indeed, they are considered to be particulate matter and ozone precursors, hence highly responsible for air pollution in industrialized areas (Kesselmeier and Staudt, 1999).

In light of this, several countries decided to adopt *ad-hoc* regulations, to prevent and control the release of industry-related VOCs into the atmosphere. In 1996, the European Union adopted a common regulatory framework, Directive 1996/61/EC, for the authorization and the control of industrial installations. This Directive has been codified in 2008

(Directive 2008/1/EC), which has been then replaced by Directive 2010/75/EU on industrial emissions, which is currently in force. The current approach has not changed substantially since 1996, and it is based on a few main principles, namely (*i*) integrated approach, (*ii*) adoption of the best available techniques, (*iii*) flexibility, and (*iv*) public participation (Directive 1996/61/EC; Directive 2008/1/EC; Directive 2010/75/EU). The regulations mentioned have defined the foundation for the prevention and the integrated control of pollution in industrial plants with potentially high environmental impact: IPPC: Integrated Pollution Prevention and Control. The basic idea behind IPPC is based on an integrated approach, aimed at defining, for each specific application, a plant solution that is feasible from both technical and economical points of view, and that allows for reducing the emissions of pollutants (O'Malley,1999). The possible strategies to achieve this goal are the following:

- The VOC emissions could be reduced at the source, by implementing cleaner production methods and technologies;
- VOC-abatement devices could be placed downstream of the production process; the most suitable technology should be identified by taking into account the cost, performance and efficiency in reducing the emissions of pollutants.

The first method is the optimal choice from the environmental point of view. However, it requires an accurate evaluation of the process and it could be not always possible to eliminate or sensibly reduce the source of pollutants.

Ethyl alcohol (ethanol) is one of the most common VOCs, and it is generated in several widespread industrial plants, like bakeries, distilleries, and foundries (Passant N.R. et al., 1993; Fatta et al., 2004). Baked products, like all yeast-leavened products, develop a certain amount of ethyl alcohol during fermentation. The quantity of ethanol produced has been found to be nearly proportional to the amount of yeast used and to the dough fermentation time (Montesinos and Navarro, 2000). The ethyl alcohol produced by the yeast metabolism remains in a liquid state inside the product, as long as the dough is kept at a temperature below 77°C. When the dough is exposed to high cooking temperatures in the oven, the ethanol vaporizes inside the bakery chamber, and it can be emitted into the atmosphere within the exhausts air flows. In the bakery industry, the only way of avoiding the production of ethanol consists of using chemical yeasts which, however, confer an unpleasant taste and a different structure to the products. For these reasons, many companies, prefer to adopt natural yeast in their recipes. The first strategy to reduce the VOC emissions, therefore, cannot be pursued, so the second approach must be followed, and the optimal VOC-abatement technique must be identified on a case-by-case basis.

In the last years, many papers focused on improving one VOC-abatement technology (Guo et al., 2021; Schnelle et al., 2015; Preis and Gregor, 2013; Huang et al., 2011; Warahena and Chuah, 2009; Schalk et al., 2005; Jeon et al., 2004; Zhao et al., 2003; Devinny et al., 1999; Kiared et al, 1996; Thair and Koh, 1996). A few researchers have reviewed the basic abatement methods, to derive practical considerations about their application (Preis et al., 2013). Other researchers have proposed a techno-economic approach, by performing an overview of the relevant cost items for several abatement techniques (Geldermann and Rentz, 2004).

The growing need to reduce the VOC emissions discharged by industrial plants requires suitable technologies, able to decrease the concentration of pollutants to comply with legal restrictions. The choice of the VOC-abatement technology for a specific industrial process must take into account several aspects, such as the chemical and physical properties of the air pollutants emitted, the concentration limits defined by the regulations, and the entity of investment and operating costs.

The technologies commonly adopted nowadays to reduce the emissions of VOCs can be grouped into two main categories: technologies based on the direct combustion of the exhaust VOCs and technologies that do not employ combustion. The combustion technologies are very effective in the abatement of VOC emissions, and they are commonly adopted in modern bakery industries. However, they are characterized by high investment and operating costs. Non-combustion technologies, on the other hand, are scarcely adopted nowadays in the bakery industry, because their possible side effects and issues often prevent their practical application. The most widespread non-combustion technologies include:

- Scrubbing;
- Condensation;
- Biofiltration;
- Carbon adsorption;
- Photolysis or photo-catalytic oxidation.

This study faces the problem of air pollution due to the VOCs produced during the baking process. After presenting an overview of the most common technologies used for the abatement of VOCs, we propose a feasibility study based on a real industrial case study. We compare the main abatement technologies from an engineering point of view, and we estimate the total cost of their implementation in a specific case study. Finally, we select the best technology for the plant considered, as the one that allows for reaching the best trade-off among legislative, environmental, and economic aspects.

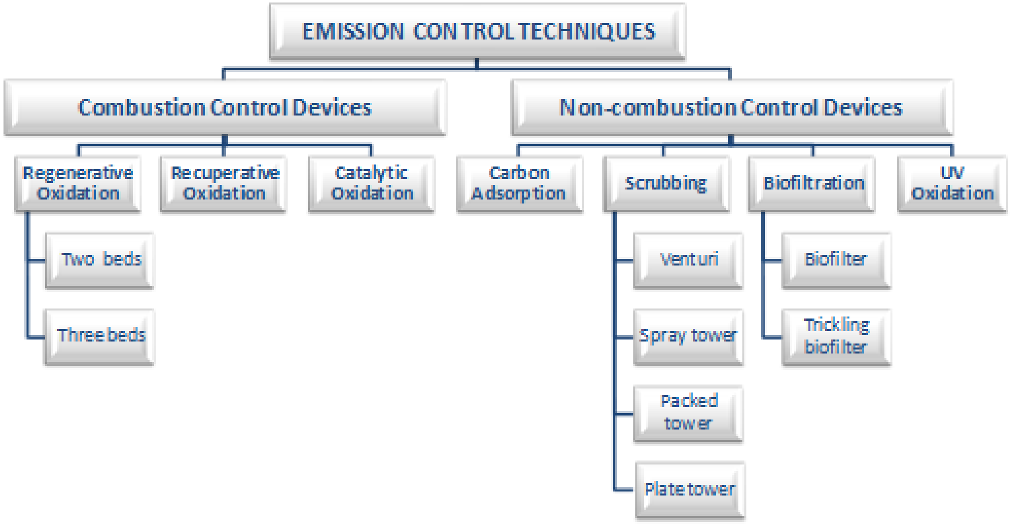

Figure 1. Overview of the main VOC-abatement technologies

2. Overview of VOC-abatement technologies

Several emission-control techniques potentially applicable to the bakery sector (i.e., they comply with the regulatory standards) are currently available on the market (Figure 1). The VOC-abatement technologies are grouped into two main categories: combustion control devices and non-combustion control devices. The main difference between them is that the technologies of the first group reduce the amount of VOCs through thermal oxidation.

This section provides an overview of the state of the art of VOC abatement systems. To carry out the overview, technology providers and end-users were interviewed. The technology providers and manufacturers were surveyed because of their knowledge of the technical solutions available in the market, and their competence in the design of VOC-abatement solutions. The end-users were consulted given their knowledge about the industrial processes, and because of their awareness of the specific characteristics and technical features required for an efficient practical implementation.

The questions covered the plant operating principles, the main cost components, the performances and the technical specifications of the systems, including the flow rate to process, the type and the concentration of pollutants and the removal rate efficiency (RRE) of the technologies. The data was processed and discussed in Sections 3 and 4.

2.1. Combustion control devices

Thermal oxidation is the most effective approach in the abatement of VOCs, as it ensures their destruction through the reaction of the pollutants with oxygen and heat. The end products of this reaction are CO_2, H_2O and heat. The destruction of VOCs is achieved at temperatures higher than 760°C, and treatment times of 0.5 to 2.0. Turbulent conditions are necessary to ensure good mixing of VOCs with air. In particular, the thermal oxidation of ethyl alcohol to CO_2 and H_2O requires exposure to temperatures of at least 870°C for 0.75 s. This temperature can be drastically reduced (to a range of 320°C to 650°C) by using a catalyst. Combustion control devices are grouped into three categories: regenerative thermal oxidation devices, recuperative thermal oxidation devices, and catalytic thermal oxidation devices.

2.1.1. Regenerative thermal oxidation devices

Regenerative thermal oxidation (RTO) systems are combustion systems where the heat is recovered inside the plant with the maximum possible efficiency. This technology is suitable for the abatement of a wide range of VOCs in a gaseous state, even at low concentrations, with a RRE of about 99%. The contaminated air is exposed to high temperatures for a period of time sufficient for the complete oxidation of VOCs, and their conversion to carbon dioxide and water vapor.

Nowadays, RTO devices are adopted in several industrial sectors such as food processing, pharmaceutical, packaging/printing, chemical, and more. Their energy consumption is limited thanks to recovery systems that use packings of ceramic material having the function of receiving the heat from the hot gas, storing it, and then emitting it back to pre-heat the inflowing gas. In this way, RTO devices allow obtaining high energy efficiency, ranging from 92% to 95%. Furthermore, they allow for minimizing the fuel consumption of the system, as the device is self-sustaining and does not require auxiliary fuel usage in the case of VOC-laden air containing fuel concentrations higher than 1.2-2 g/Nm^3.

RTO abatement systems are one of the most advanced solutions, in terms of both ecological and reliability points of view. Their main advantages are thermo-mechanical stability, abatement efficiency, flexibility, versatility, and independence from the upstream processes. Furthermore, they are not subject to corrosion and do not produce waste and by-products. Their only disadvantage, from a technical point of view, is due to the incompatibility with air containing high concentrations of pollutants.

Two types of RTO devices are currently available on the market: two-bed and three-bed oxidation devices. The operating diagrams of these devices are presented in Figure 2 and Figure 3, respectively.

In the case of a two-bed device, the basic unit is composed of the main combustion chamber provided with a burner (CC) and two recovery chambers (RC1 and RC2), containing a ceramic media bed with high heat capacity. The ceramic packings are used cyclically as pre-heaters or post-coolers, to recover the thermal energy, and their function is switched by acting on the opening of input and output valves. The process begins with one chamber (RC1) operating as a pre-heating section for the VOC-laden air and the other (RC2) as a cooling section for the purified hot air (Figure 2 - Flow conf. 1).

The contaminated air passes through RC1, where it is preheated in the ceramic media beds to a set-point temperature close to that of self-combustion of the VOC molecules contained in the stream. In the combustion chamber, the air reaches the thermal oxidation temperature and the VOCs are converted to CO_2 and H_2O. Then, the purified hot air exits the unit passing through RC2, colder than RC1. Inside RC2, the heat is removed from the air itself and stored, therefore raising the temperature of the chamber. When the temperature of RC2 reaches the set-point value, the system switches with RC2 becoming the pre-heating chamber and RC1 the cooling section (Figure 2 - Flow conf. 2). The direction of the gas flow is consequently inverted. This occurs at regular time intervals of 60 to 90 seconds.

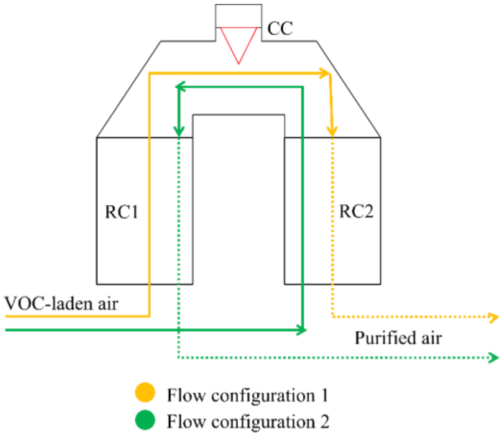

Figure 2. Two-bed regenerative thermal oxidation device.

The functioning of the three-bed system is similar, but it presents two CCs and three RCs. RC1, RC2 and CC1 work as described above, while the third ceramic bed is offline and crossed by ambient air moved by a dedicated fan (Figure 3 - Flow conf. 1). When RC2 reaches the set-point temperature, the air flow direction changes and the RC2 becomes the pre-heating chamber. At the same time, RC1 goes offline and RC3 becomes the cooling chamber (Figure 3 - Flow conf. 2). Every 60 -120 seconds the direction of the air flow is switched so that all beds have alternatively the function of pre-heating and heat recovery.

2.1.2. *Catalytic oxidation devices*

Catalytic oxidation devices (COD) are similar to RTO systems, with the difference that the abatement of pollutants occurs in the presence of a catalyst. In this way, the VOCs are converted to CO_2 and H_2O at lower temperatures, to prevent the formation of harmful by-products such as NO_x. COD devices allow for the abatement of the majority of VOCs at temperatures between 280°C and 450°C. These systems are suitable for the abatement of all non-halogenated hydrocarbons, and their RRE can reach 100%.

COD devices are used in packaging, printing, chemical and plastic industrial sectors, where high concentrations of hydrocarbons are produced. They are simple to use, flexible concerning the concentration of pollutants, and robust because of their low demand for maintenance. However, periodic replacements of the catalytic beds are required, due to the possibility of poisoning the catalyst.

In Figure 4, the operating diagram of a two-bed COD system is presented. The basic functioning is the same as described in section 2.1.1, with the addition of a catalyst, such as an inert porous substrate plated with a metal alloy containing platinum, palladium, copper, chromium, or cobalt, placed on the ceramic beds.

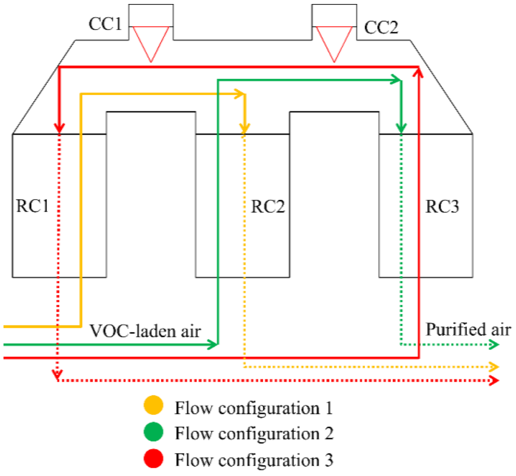

Figure 3. Three-bed regenerative thermal oxidation device.

The VOC-laden air reaches a temperature of 250-350 °C in the pre-heating RC, passes through the catalytic bed where the oxidation reaction starts, and finally reaches the CC, where its temperature increases to 400-450°C. The oxidation reaction ends when the purified air flows through RC2 towards the outlet, releasing the thermal energy. The process functions cyclically as described in Section 2.2.1.

2.1.3. Recuperative thermal oxidation devices

Similar to the previously described systems, the recuperative thermal oxidation devices are suitable for the abatement of every kind of VOC, with a RRE higher than 99%. These devices are usually adopted in industrial sectors where high concentrations of hydrocarbons are produced. The main advantages are (*i*) the possibility of recovering heat; (*ii*) the flexibility regarding the concentration of pollutants; (*iii*) low demand for maintenance and (iv) simplicity of use. On the other hand, these systems have high energy consumption in the case of air containing low concentrations of pollutants.

As shown in Figure 5, the system is composed of two shell-and-tube heat exchangers (HE1 and HE2) and one combustion chamber (CC). These systems aim to minimize fuel consumption, by using heat exchangers to recover the heat from the exhaust gas and then use it to preheat the inflowing gas.

The contaminated air is first filtered to remove the eventual solid particles, and then it flows through HE1 and HE2, where it is pre-heated to a temperature of 450-650°C by the fumes produced inside the CC, flowing counter-current. The fumes leave the system at about 350°C. The VOC-laden air flows in the CC, where it reaches the oxidation temperature of 770°C and the VOCs are converted to CO_2 and H_2O.

2.2. Non-combustion control devices

The main non-combustion abatement techniques are carbon adsorption, scrubbing, biofiltration, and UV oxidation.

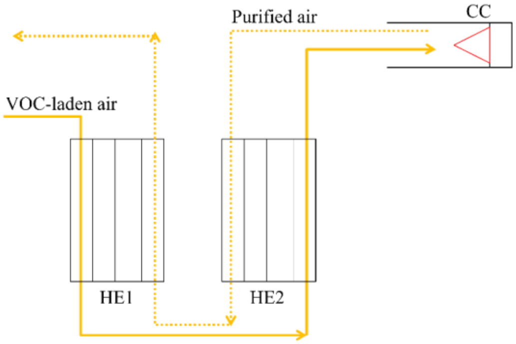

Figure 5. Recuperative thermal oxidation device.

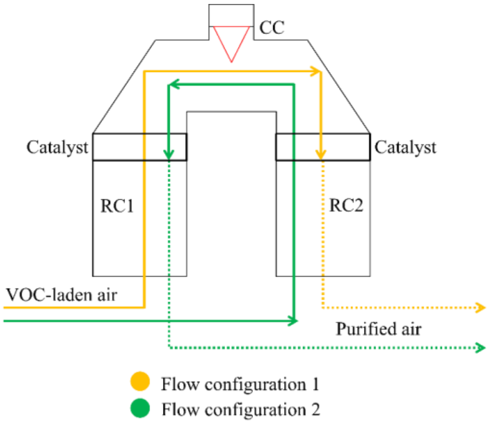

Figure 4. Catalytic oxidation device.

2.2.1. Carbon adsorption devices

Carbon adsorption devices exploit the physical adsorption on activated carbon. The main aim of these systems is to control VOCs, but they also provide results in terms of economic savings and the absence of odor emissions. CA devices are mainly adopted in industrial processes where only one solvent is used, including printing, chemical, plastic film bonding, adhesive tape production industries, and more. If correctly sized, they can achieve a RRE of about 99%. However, the device can not be used with all types of VOCs and its management may be challenging.

The solvent recovery process is composed of four main steps: (*i*) separation of the air from the solvent with adsorption on activated carbon; (*ii*) desorption of the solvent from the activated carbon through steam; (*iii*) dehydration of the solvent; (*iv*) solvent distillation. The absorption process is represented in Figure 6. The polluted air is first filtered to remove solid particles, and it is moved to the activated carbons which adsorb the solvent. The treated air can be emitted directly into the atmosphere.

When the activated carbon approaches its saturation level, its abatement efficiency significantly decreases. At fixed time intervals time, the absorption phase is therefore alternated with the desorption one. For this reason, multiple absorption units are generally employed, so when one or more units are adsorbing at least one unit can be regenerating.

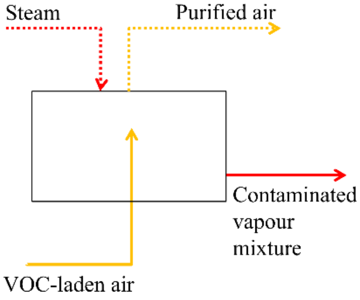

Figure 6. Carbon adsorption device.

The regeneration phase is performed by forcing a flow of steam to pass through the carbons and strip the VOCs accumulated. The mixture of VOCs and steam is then cooled down and condensed using a heat exchanger. The separation of the contaminants from the water can be achieved with a decanter, in the case of VOCs immiscible in water, or by distillation, if the VOCs are miscible in water.

Due to the difficulty in separating VOCs from the steam, this technique will not be considered in the industrial case study evaluated.

2.2.2. *Scrubbers*

Scrubbers, also defined as "washing systems", are one of the most common devices. They exploit the ability of a liquid, generally water, of absorbing gaseous pollutants, and they are suitable for water-soluble substances. The working principle of scrubbers consists in conveying the VOC-laden air into a chamber, where it comes in contact with water. The pollutants move from the air to the water and the purified air can leave the system. The main issue with the scrubbing devices is that the mixture of water and VOCs has to be disposed of. Generally, the by-products are dehydrated and buried in authorized dumps, or burned in dedicated plants. Scrubbers can be grouped into two broad categories: Venturi and tower devices. The latter can be encountered in several configurations, such as spray, packed, and plate.

The Venturi scrubbers (Figure 7) use the high velocity of the polluted gas to atomize the water, injected either at the throat or the entrance to the converging section. The VOC-laden air flow is forced through one or more annular orifices, where its velocity increases, shearing the water and forcing it to atomize in an enormous number of very tiny droplets. The velocity of the air is then forced to decrease in the diverging section, and the water droplets containing the VOCs are separated from gas by gravity. Soluble VOCs are absorbed by the water and a recovery treatment is subsequently needed, whereas the purified air can be emitted into the atmosphere.

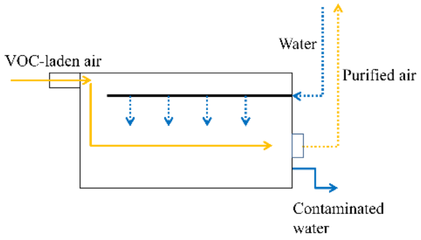

Figure 7. Venturi scrubber.

Venturi scrubbers can achieve RRE up to 96% in the case of powders, while with water-soluble substances their performance decreases. As shown in Figure 7, the device extends horizontally, so it occupies less space compared to the classic scrubber towers (Figure 8). Furthermore, these systems can include from 1 to 20 Venturi cones. Venturi scrubbers represent a good compromise between quality and price if the available space is limited, and when the gaseous flow contains a lot of solid particles. On the other hand, they are characterized by higher energy consumption compared to other scrubber systems because of the high pressure drops.

The tower scrubber (Figure 8a) is the classic scrubber system configuration, with RRE over 97%. It is composed of a vertical column containing a packed bed, whose dimensions are proportional to the flow rate of VOC-laden air. Tower scrubbers are used in chemical, pharmaceutical, and cleaning industrial sectors. They are simple to use and cheaper in terms of capital costs compared to other systems. However, as for the previous systems, large amounts of wastewater has to be treated by recovery plants. Three main types of tower scrubbers are available on the market: spray, plate, and packed towers.

The spray towers (Figure 8b) are used to purify the air from both highly soluble gases and particulate with a diameter over 5 μm. Structurally they are simple but very voluminous. They consist of a chamber in which the VOC-laden air, flowing from the bottom to the top of the system, is purified through contact with the scrubbing solution, i.e., nebulized water flowing counter-current.

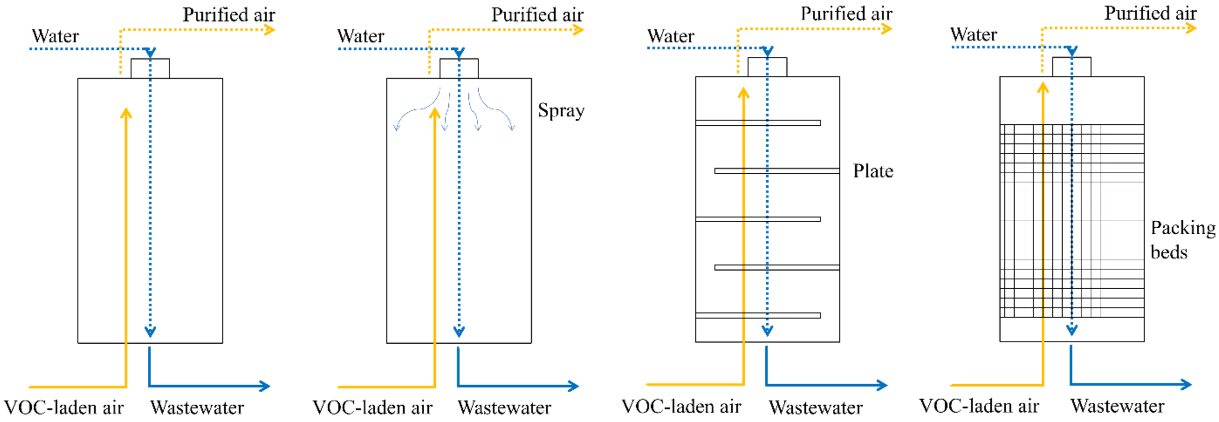

Figure 8. a) tower scrubber; b) spray tower; c) plate tower; d) packed tower.

Depending on the system configuration, the nozzles used to nebulize the water can be fixed or mobile, and positioned at one or more levels. In some configurations, the direction of the air flow can be transversal to the spray.

The plate towers (Figure 8c) are used to purify the air contaminated by gases or particulate with a diameter over 1 μm. In this case, the tower is filled with several horizontal plates with holes. The scrubbing liquid entering from the top of the tower flows downwards as a shower, while the VOC-laden air entering from the bottom flows upwards and passes through the holes. The velocity of the air flow is limited to avoid the entrainment of the liquid, especially in holes of the plates. Because of their configuration, plate towers can incur clogging problems, so they are usually designed to be easy to clean and maintain.

The packed towers (Figure 8d) are characterized by packing beds, usually made of plastic materials (but they can also be made of ceramics and metal), featuring a lot of small objects These objects, usually of elaborate shapes and with openings for the transit of the air flow, are placed on a grid at the basis of the tower. The flows of polluted air and scrubbing solution are usually counter-current, but equi-current or cross-current configurations are also available on the market. The main advantage of the packed towers is the possibility of having a large contact surface between the air and the water, which allows for an efficient abatement. These devices are suitable for both gas and vapor absorption, mainly inorganic, and for the separation of particulate at low concentrations, to avoid obstructions.

2.2.3. *Biofiltration devices*

Biofiltration devices (Figure 9) exploit the metabolism of microorganisms to break down the organic compounds present in the polluted air. They are suitable only for gases, particularly those discharged at near-ambient temperature, and their RRE ranges from 90% for monoxide to 99,9% for organic acids. These devices are commonly used in the production of fragrances, treatment of waste (landfills, sorting plants, composting), agri-food and meat processing, tanneries, farms, and by companies performing activities that involve emissions of VOCs (painting, gluing, etc.) The main advantages of this technology are the low capital and maintenance costs. The drawbacks are the sensitivity to the presence of compounds inhibiting microbial activity and the selection of the most suitable microorganism, which impact the efficiency of the process.

The principal components of this system are the pre-treatment group and the biofilter bed. The biofilter consists of an open bed containing the organic or inorganic material in which the microorganisms live: soil, bark, peat, chipped brush and inert materials are commonly used substrates.

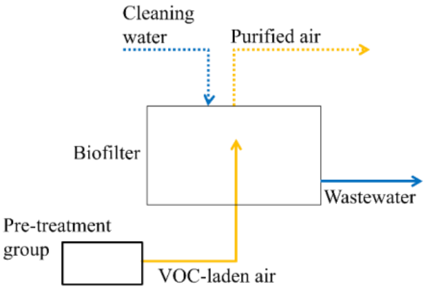

Figure 9. Biofiltration device.

The beds should be monitored to maintain suitable conditions for the survival of microorganisms. If these operating conditions are respected and the system is not subject to thermal or physical shocks, it does not require any intervention to replenish the population of the microorganisms.

The VOC-laden air flows through the pre-treatment group, where the conditions of the air, in terms of particulate concentration (<20 mg/m^3), humidity and temperature (5°C - 40°C), are adjusted to preserve the vitality of the microorganisms. The cooled-down and humidified polluted air then flows through the bed, where the microorganisms capture the organic compounds and break them down to CO_2 and H_2O through oxidation reactions. Finally, purified air can be emitted into the atmosphere. During normal functioning, the biomasses and the water with VOCs are collected at the bottom of the bed. This leachate is dragged by the cleaning water, which then needs to be properly treated.

A particular type of biofiltration technology is biotrickling. This process is similar to the common biofilter, as it is based on the metabolic activity of microorganisms, that capture the organic compounds. Differently from the standard biofiltration systems, in biotrickling devices a shell bed (CaCO3) is used as inert material to maintain the correct pH, allowing for treating gases with a high concentration of VOCs. The second difference regards the system of water collection at the basis of the bed and the absence of leachate material.

2.2.4. *Vacuum ultraviolet photolysis and photocatalytic oxidation devices*

Vacuum ultraviolet photolysis (VUV) and photocatalytic oxidation (PCO) are innovative and promising techniques for the purification of both water and polluted air, as they can degrade a broad variety of biological and gaseous contaminants into harmless end-products, such as CO_2 and H_2O), without significant energy consumption and operating at low or room temperatures. Moreover, the oxidizing effect can be enhanced by the addition of strong oxidants (ozone and/or hydrogen peroxide) or photocatalysts (pure or doped metal oxide semiconductors, generally TiO_2), which produce photo products with high oxidizing power when exposed to UV light.

The characteristics of the UV source have to be chosen based on the specific application. For example, the radiation with a wavelength of 185 nm, obtained with standard low-pressure lamps, is mainly applied in UV/O_3 or UV/H_2O_2 processes that lead to the formation of highly reactive radicals: O and OH, respectively (Schalk et al.2005). Radiation at 365 nm is more efficient than 254 nm when TiO_2/O_3/UV configuration is used to decompose toluene (Zhao et al., 2003). In the process of degradation of trichloroethylene, 315–400 nm UV-light is more favorable to photocatalytic reaction than 200–300 nm UV-light (Yu et al. 2009). The processes cited are called "photocatalysis".

Sometimes, ultraviolet radiation can be utilized standalone, since ozone is generated from the oxygen present in the ambient air UV radiation wavelengths lower than 200 nm, typically 185 nm (Huang et al. 2011). For these applications, standard low-pressure quartz lamps, in their ozone generating version (GP…VH, GPH…VH, where VH stands for very high ozone), or vacuum ultraviolet (VUV) light sources can be utilized (Schalk et al.2005, Huang et al. 2011). This process is called "photolysis".

In many practical applications, photolysis can lead to the formation of toxic by-products from incomplete oxidation of VOCs, and possible pollution caused by residual O_3. Huang et al. (2011) demonstrate that the use of a photocatalyst (TiO_2/γ-Al_2O_3/nickel foam) in addition to VUV irradiation significantly reduces residual ozone and by-products. Jeong et al. (2004) stated that the elimination of excess O_3 in the effluent gas stream can be achieved through the use of an ozone decomposition catalyst (ODC) layer set up behind the photoreactor. However, the presence of the additional ODC layer complicates the setup and adds extra costs.

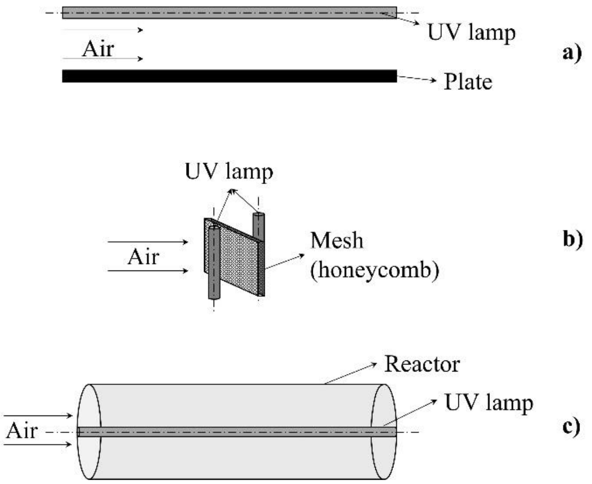

Figure 10. Different shapes of UV reactors: a) plate; b) honeycomb; c) light-in-tube.

The reactors for the treatment of polluted air can have different shapes: plate, honeycomb and light-in-tube (Figure 10). In the case of photocatalytic oxidation, the surface of the tube, the plate, or the mesh is coated with the catalyst (i.e. nanometer TiO_2 powder).

3. Materials and methods

3.1. Nomenclature

The symbols and the abbreviations adopted in the paper are summarized below in Table 1.

Table 1. Symbols and abbreviations adopted in the paper.

Term	Description
$\dot{V}$	Volumetric flow rate
K	Lower calorific value
C	Annual cost
c	Unitary cost
i	Discount rate
τ	Discount coefficient
n	Useful life
h	Annual operating hours
P	Power
Subscripts	
CH_4	methane
et	ethanol
el	electricity
fc	Fuel consumption
ec	Electric consumption
wc	Water consumption
pm	Preventive maintenance
r	Replacement of the catalyst or filter medium
regime	Regime condition
trans	Transient condition
o	operating
inv	investment
tot	total

3.2. Industrial case study

In this section, a feasibility study referring to an industrial bakery plant is presented. As mentioned in the previous sections, in the case of baked products, a certain amount of ethyl alcohol (one of the most common VOCs) is generated during the fermentation process. The exhaust fumes discharged by the baking ovens, therefore, must be treated to comply with the legislative restrictions in terms of the total amount of VOCs emitted.

The concentration of VOCs and the air flow rate are fundamental variables to identify the RRE required to comply with the legislative emission limits; hence, from the engineering point of view, these two parameters are the key factors in the choice and the sizing of the abatement system. To identify the best technology, it is also essential to consider its applicability. The optimal abatement technology is represented by the solution which allows for meeting the legal requirements and achieving the best trade-off between environmental and economic aspects.

3.2.1. Industrial bakery plant

The bakery plant analyzed, located in northern Italy, is equipped with two chimneys emitting the exhaust fumes produced in the baking chamber. The gas flow is captured and conveyed into a duct, connected to the abatement system. The gas discharged contains ethanol, the emissions of which must be limited to 50 mg/Nm^3. The characteristics of the plant emissions are presented in Table 2.

Table 2 Physical and chemical characteristics of the fumes

Item	Quantity	Units
baking chamber exhaust fumes mass flow rate	1710	kg/h
baking chamber exhaust fumes temperature	140	°C
Ethyl alcohol mass flow rate	2500	g/h
Ethyl alcohol lower calorific value	26790	kJ/kg
Water content	0.25	kg/kg$_{a,d.b.}$

3.2.2. Feasibility study

To determine the best technique for the abatement of the VOCs emitted by the bakery plant, five different technologies currently available on the market were evaluated with a techno-economic analysis: (*i*) thermal oxidation; (*ii*) catalytic oxidation; (*iii*) biofiltration; (*iv*) scrubbers; (*v*) photocatalytic oxidation.

An economic evaluation of the technologies, including operating and investment costs, was carried out according to the procedure described in this section. As mentioned in Section 2, the data used was obtained through commercial research, during which the suppliers and the end-users of VOC-abatement systems were consulted.

For each device, a 40% markup on the investment cost was considered to account for the additional costs (i.e. installation, assistance to installation, rental of special equipment, consultancy for safety measures, etc.). The resulting investment cost was then discounted, considering a discount coefficient calculated as:

$$\tau = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \tag{1}$$

A useful life (n) of 20 years and a rate (i) of 5% were considered for all the plants.

The annual operating costs were calculated considering a daily production time of 24 hours and 300 working days per year. Methane cost of 0.3913 €/Nm3, electric energy cost of 0.1654 €/kWh, and water cost of 1 €/m3 were assumed, based on Eurostat 2021 data, referring to a consumption range between 10000 GJ and 100000 GJ for methane and between 2000 MWh and 20000 MWh for electric energy.

Concerning combustion oxidation devices, it is important to consider that the discharge gas of the bakery plant contains ethyl alcohol, characterized by a given lower calorific value (Table 2). The presence of ethanol allows for saving a certain amount of methane, which was estimated with the following function, assuming K_{CH_4} = 35797 kJ/Nm^3:

$$\Delta\dot{V}_{CH_4} = \frac{\dot{V}_{et} \cdot K_{et}}{K_{CH_4}} \tag{2}$$

The cost of fuel, under steady-state operating conditions, was calculated as follows:

$$C_{fc-regime} = \dot{V}_{CH_4-regime} \cdot h \cdot c_{CH_4} \tag{3}$$

For each configuration, 52 start-ups per year (one for each week) and a start-up time of 45 minutes were assumed. During the start-up, the consumption of methane is higher compared to steady-state conditions. For each thermal device, the fuel cost under transient operating conditions was computed as:

$$C_{fc-trans} = \dot{V}_{CH_4-trans} \cdot h \cdot c_{CH_4} \tag{4}$$

The total annual fuel cost results from summing the costs for stationary and transient operating conditions.

The cost related to electricity consumption was calculated based on the electric power absorbed by the plant during the operating time.

$$C_{ec} = P_{el} \cdot h \cdot c_{el} \tag{5}$$

For the calculation of maintenance cost, the labor-related cost of a skilled worker was calculated assuming 10 hours of work per day, two working days, and a gross salary of 50 €/h. Additional contributions for travel and meals and lodging were considered, amounting to 400 € and 200 €, respectively. The maintenance cost, for all devices, resulted to be 1600 €/y.

The cost for the substitution of the catalyst bed was calculated based on the cost of the single substitution and the number of substitutions per year.

As regards non-thermal oxidation devices, they reduce VOCs through biological fermentation (biofiltration and biotrickling) or absorption with water, without thermal oxidation. For this reason, the operating costs did not include any fuel consumption. However, water consumption, proportional to the volume of the system, must be considered, as it is necessary to maintain an appropriate degree of humidity inside the device. In addition, the cost of the replacement of the filter medium must be taken into account.

Table 3. Summary of the costs associated with each technology

VOCs abatement technology	C_{fc} [k€/y]	C_{ec} [k€/y]	C_{wc} [k€/y]	C_{pm} [k€/y]	C_{r} [k€/y]	**C_{o} [k€/y]**	**C_{inv} [k€/y]**	**C_{tot} [k€/y]**
Three beds regenerative thermal oxidation	8.1	9.0		1.6		**18.7**	**13.0**	**31.6**
Two beds regenerative thermal oxidation	9.5	6.0		1.6		**17.1**	**14.6**	**31.7**
Catalytic Oxidation	3.9	6.0		1.6	1.8	**13.3**	**15.2**	**28.5**
Biofiltration		7.1	0.5	1.6	0.5	**9.7**	**5.1**	**14.8**
Biotrickling		6.0	0.5	1.6	3.0	**11.1**	**8.5**	**19.6**
Scrubber		0.7	0.7	1.6		**3.0**	**7.3**	**10.3**
VUV module		3.0		1.6		**4.6**	**1.0**	**5.6**

4. Results and discussion

The costs associated with the technologies evaluated are reported in Table 3.

As stated, the optimal abatement technology is the one that allows for reaching the best compromise between legislative, environmental, and economic aspects. All systems considered in the feasibility study are capable of meeting the legislative limit of 50 mg/Nm^3 on VOC emissions, so the best solution was determined based on economic convenience.

Combustion control devices did not appear to be an advantageous option, because the concentration of VOCs in the exhaust gas of the baking oven considered was not sufficient to allow for the self-sustenance of the burners. Therefore, these devices would have required methane supply, thus becoming more expensive compared to other technologies.

Biofiltration systems were also considered unsuitable because they usually generate waste and bad odors, not appropriate in the case of a food plant.

The abatement of VOCs with scrubbers had the drawback of producing a large amount of wastewater, which must be treated before its disposal. In the case study considered, the plant was already equipped with a water purifier, so the cost due to the wastewater treatment and disposal was not taken into account. Despite this, scrubbers did not result to be the most cost-effective solution.

In conclusion, the best technology for the bakery plant considered turned out to be the vacuum ultraviolet module, which is characterized by a competitive cost and the ability to effectively treat VOC-laden air.

5. Conclusions

In this paper, we addressed the issue of the alteration of the air quality due to the VOCs released by an industrial bakery plant located in northern Italy. An overview of the topic and general legislation is presented, followed by a detailed review of the most common systems for VOC reduction.

Several abatement systems are available on the market, but in light of the presence of ethyl alcohol in the exhaust air flow of the bakery plant, five technologies have been evaluated to select the optimal one: (*i*) thermal oxidation; (*ii*) catalytic oxidation; (*iii*) biofiltration; (*iv*) scrubbers; (*v*) photocatalytic oxidation.

For each technology, both technical and economic evaluations were carried out based on the data obtained by interviewing technical providers of VOC-abatement systems and end-users of these technologies.

From the evaluation performed, the optimal technology for the industrial bakery plant considered resulted to be photocatalytic oxidation.

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