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Biofiltration of Contaminated Air – Current Status, Development Trends

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1. Introduction

Most of the production processes are accompanied by the emission of various waste, in particular waste gases. Among the methods of their purification, biofiltration plays an increasingly important role. Its essence is the distribution of air pollutants by microorganisms, deposited on a solid carrier. Consortia of microorganisms composed of both, fungi and bacteria cover the surface of the carrier with a biofilm. Biofilms form microorganisms that adhere to each other as well as to the surface of the bed through secreted mucus. Organized this way, they work efficiently and are able to survive adverse periods of hunger, dryness, extreme temperatures or intoxication with toxins (Sauer 2017).

In biological methods of gas cleaning, we can distinguish typical solutions such as biofilter and biotrickling filter. The biofilter bed are only moistened, while in biotrickling filter aqueous solution of the medium is assured all the time on bed, what provides ensuring adequate hydration and supply of elements necessary for microorganisms, absent occur in the stream of purified gases. The success of gases cleaning depends on many factors, such as the material, structure, moisture content of the bed and the gas to be purified, as well as temperature, pH, nutrients and the concentration of impurities at the inlet. Due to the fact that biofiltration is a biological method, on the assumption is intended to be pollution must be biodegradable.

2. Area of application

Primary and natural applications of biofiltration are air deodorisation and waste gas treatment from other biological processes, such as composting, and wastewater treatment. This is a consequence of the fact that, this method works best for humid gases with a low concentration of easily biodegradable pollutants, released in the mentioned processes. Later, it was used to remove impurities in higher concentrations, xenobiotic and inorganic substances and in case of hot and dry gases.

In the literature, we can find many descriptions of both research work and the practical use of biofiltration (Cheng Z. et al. 2016a, Hernández et al. 2010, Liao et al. 2015, Rodriguez et al. 2014). The range of removals of pollution is also very wide. Among them are saturated and unsaturated, aliphatic and aromatic hydrocarbons, occurring both individually and in mixtures, such as toluene, xylenes, trimethylbenzenes, and styrene (Hu et al. 2015, Liao et al. 2015, Paca et al. 2012, Rene et al. 2010, Rodriguez et al. 2014, Wang et al. 2015, Xi et al. 2014). Also presented are organic compounds with oxygen in the molecule, synthetic and natural in origin such as formaldehyde, ethyl acetate, acetone, methyl ketone, alpha-pinene (Cabeza et al. 2013, García-Pérez et al. 2013, Li et al. 2012, Zare et al. 2012), with nitrogen in the molecule like triethylamine (Gandu et al. 2013), with sulfur in a molecule like thiols (mercaptans) and organic sulphides (Hernández et al. 2010, Lebrero et al. 2012), or hardly degradable chlorosubstituted substances such as trichloroethene, chloroform, and chlorobenzene (Balasubramanian et al. 2011, Balasubramanian et al. 2012, Liao et al. 2015, Shukla et al. 2010). Inorganic compounds such as hydrogen sulphide and ammonia are also removed by biofiltration (Hernández et al. 2010, Maestre et al. 2010). The biofiltration was also subjected to air contaminated with multi-component mixtures containing organic and less inorganic compounds found in various combinations. For example: benzene, toluene, chlorobenzene, ethylbenzene, m- / o- / p-xylene, styrene, benzoic aldehyde, 1,2,3- / 1,2,4- / 1,3,5-trimethylbenzene, n-acetate butyl, DMS (dimethyl sulfide), DMDS (dimethyl disulfide), MEK (methyl ethyl ketone), MIBK (methyl isobutyl ketone), ammonia, methanethiol, α-pinene, hexane, styrene, acetone, ammonia, nitrogen oxides, and hydrogen sulphide (Hernández et al. 2010, Hu et al. 2015, Lebrero et al. 2012, Lebrero et al. 2010, Li et al. 2012, Liao et al. 2015, Sempere et al. 2010, Wieczorek 2005).

3. Biofilter – division, construction, operation

Taking into account the principle of operation, biofilters are divided into typical biofilter (classic) and biotrickling filter (Rybarczyk et al. 2019, Mudliar et al. 2010). The construction of a biofilter, and actually a bioreactor, is very similar to an adsorber. The main difference is that the adsorber only traps contaminants and the biofilter traps and decomposes them, as a result of microorganisms (Nanda et al. 2012, Ralebitso-senior et al. 2012). Due to the specificity of the process, packing material of non-biological filters are kept dry, and biofilters wet, which is a prerequisite for colonization by microorganisms (Showqi et al. 2016). By colonizing a bed, microorganisms produce a moist film on its surface called biofilm, which provides them with favourable conditions for the development and survival of stressful situations, e. g. dryness, poisoning (Sauer 2017). The efficiency and effectiveness of biofiltration depends on the parameters of gas flow, its composition and conditions in the packing material in which these microorganisms are present (Kumar et al. 2011). These include gas flow rate, pollutant concentration, type of pollutant and its properties, temperature and humidity of gases and deposits, bed texture, availability of oxygen, salinity, and pH of the deposit, as well as availability of nutrients not found in the treated gases (Varjani 2017). Biotrickling filters are equipped trickle bed with a nutrients for microorganisms, which is a solution of suitable minerals and in some cases, different organic substances such as vitamins and minerals. Their packing material are generally composed on the basis of inert mineral or polymeric materials. Biofilter bed are usually based on biodegradable organic material. Such materials are also susceptible to easily occurring abiotic degradation (Lebrero et al. 2010). Polluted air or other ventilation gases directed to the biofilter bed should be free of excessive amounts of dust, their humidity should not be less than 90%, and the temperature should not be higher than 40°C. If these requirements are not met, the gases require pre-conditioning, in particular dust extraction and through humidification. A typical industrial biofilter has the shape of a short, rectangular or cylindrical column with a grate at the bottom. There is packaging material on the grate, above which the system of spraying nozzles is mounted. The biodegradation process of pollutants on the bed in a biofilter usually takes place under aerobic conditions, and local oxygen deficiency is treated as one of the reasons for the low efficiency of the process. In some situations, however, lack of oxygen is a positive phenomenon. For example, biofiltration of biogas to remove hydrogen sulphide from biogas under aerobic conditions is dangerous because of the possibility of explosion (Fernández et al. 2013). Designing industrial biofilters, contrary to appearances, is not a simple activity. It is relatively easy to design a biofilter designed for the purification of gases from other biological processes, such as sewage treatment or composting. The waste gases originating from them are moist, their impurities are biodegradable and these concentrations are lower than toxic. In such cases, it is sufficient to base the design process on well-established principles recorded in the available engineering and scientific literature. In the case of waste gases contaminated by gases and vapours of xenobiotic substances or containing dust particles with unknown, often toxic properties, this is a difficult process and should be preceded by tests to limit the possibility of large errors.

4. Packing materials for biofiltration

The most important features of packing material, which is a key element of the biofilter, are the high specific surface area necessary for the development of microorganisms (Anet et al. 2013), porosity ensuring homogeneous distribution of gases, low flow resistance, and good water retention, as well as appropriate mechanical properties (Gutiérrez-Acosta et al. 2012, Lebrero et al. 2012) and also low price (Li et al. 2012).

The beds of Biofilter are composed on the basis of natural products, both organic and inorganic, synthetic materials and mixtures of natural and synthetic products. Typical organic materials of natural origin include compost, peat, wood chips, and bark, coconut fibres (Dorado et al. 2010). Less typical are dried corn cobs (Rahul et al. 2013), and walnut shells (Zare et al. 2012). Among natural and synthetic mineral materials we can find lava rock (Rene et al. 2011), vermiculite (Brandt et al. 2016), perlite (Xi et al. 2014, Schmidt & Anderson 2017), obtained from natural silicates maifanit (Chen X. et al. 2016), poraver (García-Pérez et al. 2013), and wood charcoal (Singh K. et al. 2010). The hybrid materials include mixtures and composites from activated carbon, wheat bran and sawdust in the ratio 1:2:1 (Cheng Z. et al. 2016b), scorii and compost (Rodriguez et al. 2014), coral rock, bark, keramzite, coal and compost in proportions 160:120:100:60:15 (Sun et al. 2012), keramzite and compost (Hernández et al. 2010), high-density polyethylene and fibers of Agave in the ratio 70:30 (Robledo-Ortíz et al. 2011). The latter also includes deposits of synthetic polymers of the polyvinyl chloride type (Balasubramanian et al. 2012), polypropylene Pall rings (Fernández et al. 2013), also polyurethane foam (Singh R. et al. 2010). The bed, adapted to the needs, increases the efficiency of biofiltration and facilitates its management.

5. Microorganisms

Initial, to move into on biofilter beds microorganisms capable of decomposition of air pollution is achieved in two ways. The first, largely natural, consists in filling the chamber of the apparatus with the packing material, preferably already richly inhabited by microorganisms, for instance compost and to start in motion air flow the polluted. As a result of the natural selection of microorganisms presented, in the material of the bed and applied to them along with the flowing air, a consortium of microorganisms degrading the pollutants is formed. The second way depends on the inoculation of fresh packing material from an admixture of an overworked the bed or other material containing microorganisms for instance sewage sludge or a specially prepared vaccine. It can be expected that the effect of vaccination will be better if the biofiltration conditions as well as the composition and concentration of contaminants will be closer to those used during the preparation of the vaccine. Almost twenty years of experience of one of the authors in biofiltration and biofilter exploitation indicates, however, that there are no obvious, benefits achieved by inoculating the deposit. Biofilters by nature operate under non-sterile conditions, so that microorganisms colonizing the packaging material at a given time are subjected to constant pressure from external microorganisms flowing mainly from the air flowing through them. In many cases, frequent and unexpected changes in the morphology of the microorganisms inhabiting the bed are easily noticeable even with a naked eye (Fig. 1). Changes in stuff the microbial of the packing material, and in particular in the proportional of quantitative microorganisms, may also cause environmental factors. For example, (Borin et al. 2006) describe changes in the microbial density ratio along the column height and also with the change in relation to the benzene load. In this situation, the grafting of the bed can only be significant if the pollutants to be eliminated by biofiltration are broken down by microorganisms rarely found in a given geographical location. The lack of suitable microorganisms in the environment results with an unacceptable waiting time for the biofilter to start working effectively.

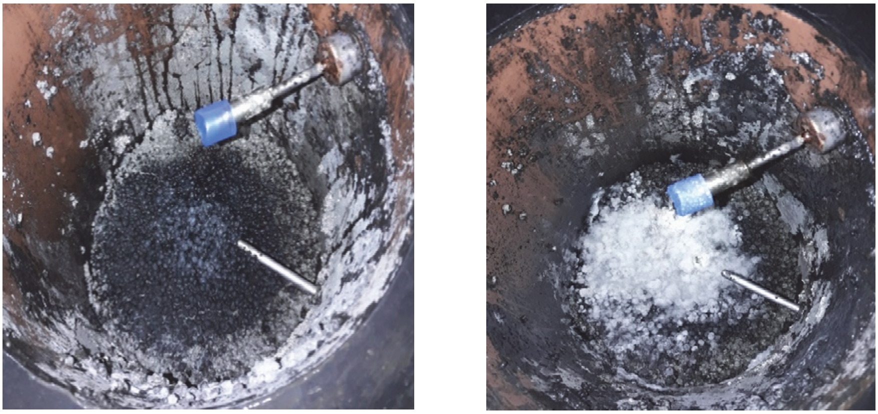

Fig. 1. A bed of biofiltration column inhabited by a consortium of microorganisms;
Left drawing 4 days after the introduction of the substance.
Right drawing 10 days after the introduction of the substance (own photograph)

Such contaminants include commonly used anti-knock additives for unleaded petrol, for example some aliphatic ethers (Fortin & Deshusses 1999, Wieczorek et al. 2013). It seems, however, that for undisturbed operation of biofilters it is more important to ensure proper biofiltration conditions, especially temperature and humidity of both purified gases and biofilter beds, than vaccination.

In the case of vaccine preparation, active microorganisms specialized in the degradation of specific contaminants (chemical compounds) are obtained mainly by screening from the natural environment, preferably contaminated with substances to be filtered out. In addition, microorganisms are extracted from composting biomass, sediments from sewage treatment plants or from the bed of exploited biofilters. Another source of such microorganisms may be soils polluted with oil, and soils located in the vicinity of pollution emission sources (Liao et al. 2015, García-Pérez et al. 2013). Activeies sewage sludge from industrial wastewater treatment plants, e.g. from the pharmaceutical industry (Wang et al. 2015, Xi et al. 2014) or refineries (Rene et al. 2012), can also be used for the same purpose.

In order to achieve the assumed degradation activity of biofilter bed, various strategies of management are applied. Typically, after loading of the fresh bed, and especially at the first start-up of a biofilter, low loads are applied, by feeding gases at low speed or by lowering the concentration of contaminants, either by lowering the concentration and flow rate at the same time. However, we can find, descriptions of procedures when the opposite was done, where a high concentrations of pollutants was used initially applied and then lowered (Zamir et al. 2012). The initial period of operation of a biofilter is called its adaptation. During this time, there are changes in the numbers, composition and properties of the microorganisms consortium also occurs changes in the properties of the bed material, e. g. release of biogenic elements as a result of chemical and biochemical transformations. For microorganisms that break down hydrocarbons directly, adaptation consists of: induction or depression (inhibition) of specific enzymes, genetic changes resulting in modification of metabolic pathways and selective enrichment in microorganisms capable of metabolising hydrocarbons (Chikere et al. 2011). One of the main factor condition of genetic transformations in bacteria is horizontal gene transfer (Obayori & Salam 2010). Another way to obtain microorganisms that are effective in the biodegradation of specific substances is to acclimatize them in a bioreactor beforehand. For example, Amin or Lebrero and their associates, used a bioreactor fed with a nutrient solution with periodical addition of the compound of interest (Amin et al. 2014, Lebrero et al. 2012). All these activities are aimed have the breed a consortium of microorganisms that effectively break down selected pollutants.

The period of acclimatization of microorganisms to the conditions prevailing in the deposit may last from a few weeks to several months (Rahul et al. 2013, Hernández et al. 2010). Microorganisms that to populate biofilter beds can form consortia that are typically fungal or bacterial as well as mixed (Revah et al. 2011, Estrada et al. 2013, Cheng Z. et al. 2016b, Vergara-Fernández et al. 2018) capable of biological gas purification. A number of interesting information was obtained during the research, carried out by various methods and techniques, including molecular biology, aimed at the identification of microorganisms and their consortia biodegrading individual impurities or their mixtures. An exemplary statement of microorganisms and break down a pollutants by them is presented in Table 1. A different summary of microorganisms and degraded substances by them, with divided into aliphatic, monoaromatic, polyaromatic and resin hydrocarbons, we can find in the work of (Varjani 2017).

Table 1. Microorganisms degrading environmental pollutions

Microorganisms	Pollution	Author
Candidia tropicalis, Phialophora Trichoderma viride	Toluen	(Song et al. 2012) (Zhai et al. 2017) (Cheng Z. at al. 2016b)
Pseudomonas sp.	Styren	(Kasperczyk et al. 2012)
Sporothrix variecibaus	Styren	(Rene et al. 2011)
Pandoraea sp. JB1, *Xanthomonadales bacterium*	Styren, toluen, aceton, MEK	(Li et al. 2012)
Exophiala sp.	BTEX	(Rene et al. 2012)
Pseudoxanthomonas spandix BD-a59	BTEX	(Choi et al. 2013)
Janibacter sp.	BTEX	(Jin et al. 2013)
Strain FMB08 9, *P. putida* F1*, Echerichia coli* DH5a	BTEX	(Morlett-Chávez et al. 2010)
Pseudomonas Putida F1	B,T,o-X	(Robledo-Ortíz et al. 2011)
Mycovacterium cosmeticum byf-4	B,T,E,o-X	(Zhang L. et al. 2013)
Ralstonia picketii L2	Chlorobenzen	(Zhang L. L. et al. 2011)

As it was shown, many groups of microorganisms participate in the catabolytic degradation of hydrocarbons and their derivatives. Initially it was assumed that this process takes place only in the presence of oxygen, netheless some microorganisms are capable of such action also in anaerobic conditions (Abbasian et al. 2015, Meckenstock et al. 2016). Reactions typical for both metabolic pathways are oxidation and reduction, hydroxylation and dehydrogenation (Abbasian et al. 2015, Wilkes et al. 2016). As a result of progressive degradation in the reaction environment, the proportion of polar fractions grow, and the proportion of saturated and aromatic hydrocarbons to decline (Varjani 2017). Biodegradation by bacteria a aliphatic hydrocarbons that can be considered as representatives of the whole family of organic compounds is usually initiated by oxidation involving a system of monooxygenase or dioxygenase - electron conveyor (various forms of NADH nicotine-amidoadenine dinucleotide) according to two paths.

On the first of them, during the reaction (Fig. 2), the oxygen atom is attached to the hydrocarbon, which leads to the formation of an appropriate I-order alcohol (Abbasian et al. 2015, Chikere et al. 2011) oxidized at subsequent stages to aldehyde and fatty acid. According to the second, dioxygenase attacks the extreme (terminal) methyl group, allowing it to attach two oxygen atoms with the formation of peroxide, which is then converted through alcohol and aldehyde to fatty acid.

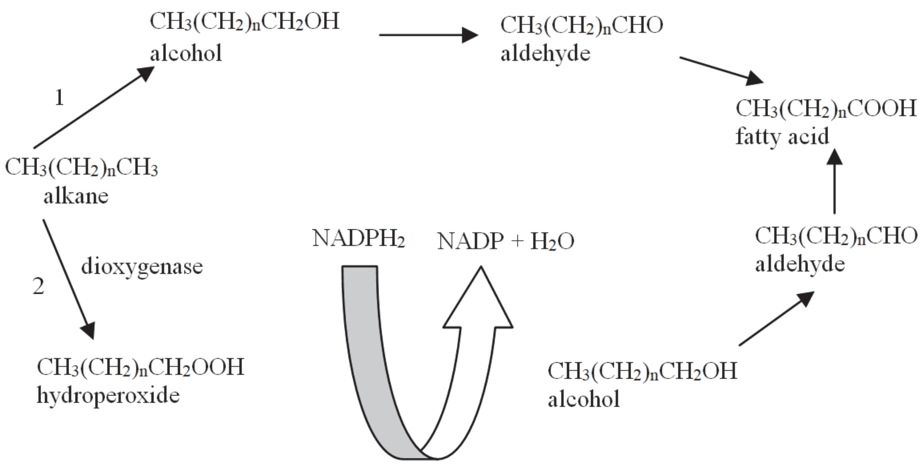

Fig. 2. Diagram of biodegradation of alkanes (Chikere et al. 2011). 1 – pathway 1, 2 – pathway 2, NADP - nicotinamide adenine dinucleotide phosphate, $NADPH_2$ – nicotinamide-adenine dinucleotide phosphate (reduced)

The resulting fatty acid, regardless of pathway, is further metabolised according to the β-oxidation mechanism specific to live cells to acetyl or propionyl coenzyme A (CoA). These compounds are further metabolized in the tricarboxylic acids cycle (TCA or Krebs cycle) to CO_2 and H_2O. In this way, the methyl group can be oxidized at the end of the chaine of alkanes, the methylene group adjacent to the extreme methyl group and the two extreme methyl groups, respectively terminal oxidation, sub-terminal oxidation and ω-oxidation (di-terminal oxidation) (Fig. 3).

More information on the biodegradation of alkanes and alkenes as well as descriptions for branched alkanes and cycloalkanes can be found in the works of other authors such as Abbasian and his contributors (Abbasian et al. 2015) or (Kwapisz 2006).

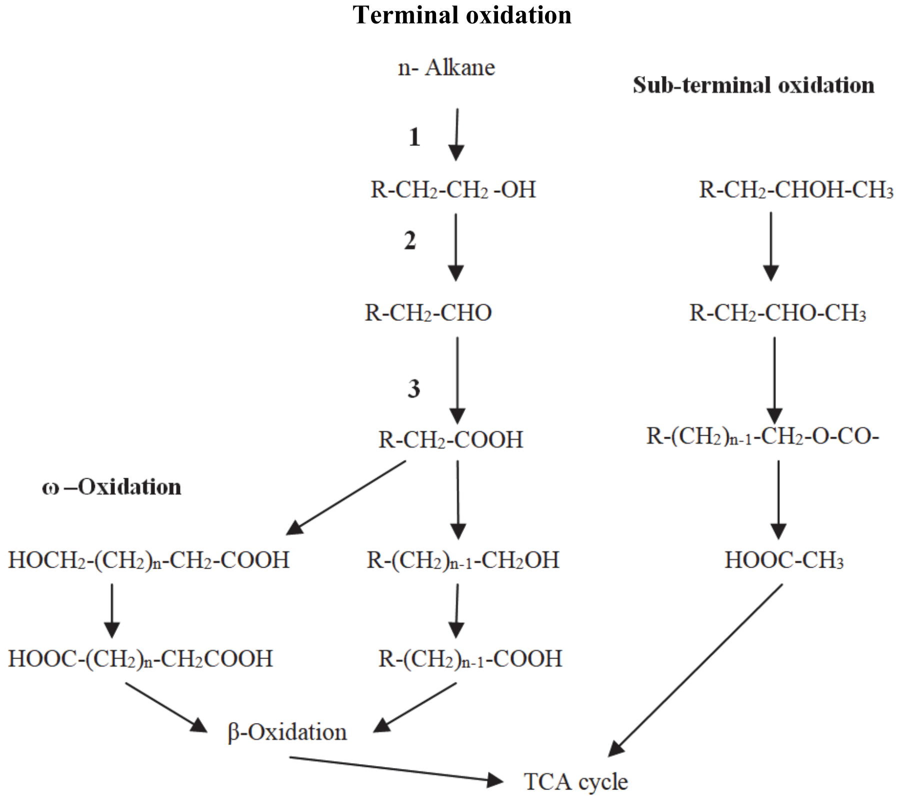

Fig. 3. Possible paths of aerobic biodegradation of n-alkanes (Abbasian et al. 2015, Varjani 2017). 1 – n-alkane monooxygenase, 2 – alcohol dehydrogenase, 3 – aldehyde dehydrogeanse

Biodegradation of aromatic hydrocarbons, especially polycyclic hydrocarbons (PAHs), is significantly hampered by their greater chemical stability, very poor water solubility, the formation of metabolites toxic to microorganisms and the co-occurrence of more easily decomposable substances or the lack of suitable cometabolites (Chikere et al. 2011). So far, no microorganisms have been found to degrade polycyclic aromatic hydrocarbons by themselves. They are broken down in cometabolic processes (Van Elsas et al. 2007). In order for aromas to biodegradation, molecular oxygen is necessary for enzyme assisted attack on the PAH ring. Catalyzed by dioxygenase, oxidation with aerobic bacteria enables the transformation of arenas into cis-dihydrodioles with neighbouring hydroxyl groups. (Sun et al. 2012). In the next step, as a result of the action of appropriate dihydrogenases, the dihydrodiols ring is cleaved between carbon atoms substituted hydroxyl groups or between carbon atoms bound to hydroxyl groups and adjacent carbon without this group. These reactions are called respectively ortho- and meta- split (Chikere et al. 2011, Padhi & Gokhale 2016, Van Elsas et al. 2007). Some derivatives of aromatic hydrocarbons, e. g. styrene, are broken down in the same way (Przybulewska & Wieczorek 2006).

Considering the enormous number of organic compounds, it is impossible to present in one work even only the most typical examples of biodegradation paths occurring in biofilters during their operation. In most cases, when it is necessary to answer how this process takes place, it will be necessary to search for appropriate literature indications and possible research works.

6. Additives improving the bioavailability

Most of the pollutants removed by biofiltration are organic compounds, which of many are difficult to dissolve in water, and thus also in fluids and cellular secretions. This makes it much more difficult to transfer contaminants from the gas stream to the biofilm and further into the cells, in other words, reduces their bioavailability. One way, to increase the performance of biofiltration is to use special additives to improve bioavailability, and as a result efficiency of the biodegradation. The addition of organic substances such as surfactants, in particular Tween 20 (Cheng Y. et al. 2016, Avalos Ramirez et al. 2012), Triton X-100 (Sówka et al. 2016a), β-cyclodextrin (Sówka et al. 2016b), silicone oil (Shukla et al. 2010) or methanol (Zehraoui et al. 2012) can be distinguished.

These additives sometimes also improve the stability of the biofiltration process.

7. Construction novelties - an exemplary solutions

Biofilters, in comparison with conventional gases stream cleaning devices, have large cross-sectional areas, which makes uniform flow of the purified gases stream difficult and humidification of the bed. These problems could be alleviated by the use of biofilters with a rotating drum (Chen J. et al. 2016, Padhi & Gokhale 2016). Figure 4 shows such a device developed by Chen with co-workers (Chen J. et al. 2016). Biofilters with a rotating drum are more costly, both at the investment stage and on move.

This can be avoided by using a tubular biological filters with a fixed cylindrical bed (Fig. 5) proposed by Chen with co-workers (Chen et al. 2012). That solution works well during the treatment of waste gases with low concentrations of pollutants even at high flow rates and long-term operation.

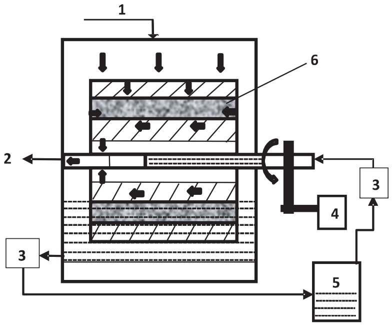

Fig. 4. Biofilter diagram with a rotating drum (Chen J. et al. 2016). 1 – polluted air, 2 – purified air, 3 – metering pump, 4 – motor , 5 – nutrients reservoir, 6 – biofilter bed

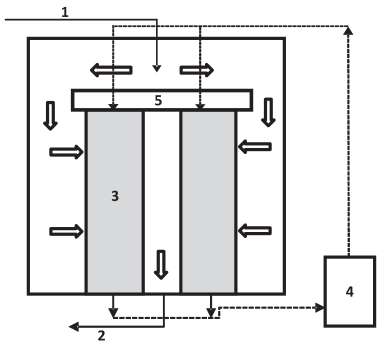

Fig. 5. Diagram of a tubular biological filter (Chen et al. 2012). 1 – polluted air, 2 – purified air, 3 – thick walled tube of polyurethane foam, 4 – nutrient solution tank, 5 – nutrient solution distributor

8. Hybrid systems

One of the more known solutions of hybrid systems type are biofilters equipped with a buffer in the form of a pre-filter with active carbon (Chang et al. 2015, Sempere et al. 2010). A novelty is the biofiltration system supported by photocatalytic oxidation (Hinojosa-Reyes et al. 2012, Wei et al. 2010). Photodegradation and biofiltration have been integrated to improve the efficiency of the removal of resistant contaminants. The intermediates of photodegra-dation of pollutants flow to the biofilter where they are biologically subject to decomposed.

UV pre-treatment not only improves the removal of contaminants, but also has a positive impact on the microbiological community (Jianming et al. 2014). Such solutions have been checked on a pilot scale. Multi-component mixtures of volatile organic compounds were eliminated efficiently and ecologically (He et al. 2012).

The idea for the future is to use biofiltration for simultaneous generation of electric current. The integrated BF-MFC (biotricklin filter–microbial fuel cells) system (Fig. 6) combines the biodegradation of off-gas pollution with the generation of electricity.

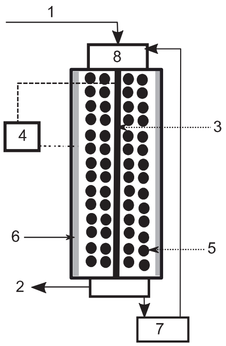

Fig. 6. Diagram of a biofilter with generation of electric current (Wu et al. 2016). 1 – polluted air, 2 – purified air, 3 – anode (graphite), 4 – multimeter, 5 – bed (coke), 6 – polymer cathode, 7 – water tank, 8 – sprinkler

According to the classical scheme, electrons are released in the process of anaerobic decomposition of contaminants by microorganisms, which are then transferred to the anode directly or with the aid of a mediator. On the cathode there is a reaction of oxygen with protons and electrons returning, throughout the external circuit (Evelyn et al. 2014). According to Wu et al. (Wu et al. 2016), the mechanism proposed by Evelyn et al. (Evelyn et al. 2014) by which metabolites with electron transfer function are produced during biofiltration is unsatisfactory. Therefore, another solution, taking into consideration the presence of a gas diffusion layer, in which waste gas diffuses into an anode converting it into electric current has been proposed (Wu et al. 2016). The packing material in such a biofilter should exhibit the characteristics of a good carrier for microorganisms and demonstrate electrical conductivity, which is necessary to serve as a cathode of a microbial fuel cell forming an oxygen electrode with the oxygen reducing on it. Coke (Wu & Lin 2016), high-performance activated carbon (Janicek et al. 2015) and graphite (Wu et al. 2016) are used for this purpose, among others.

9. Summary

Biofiltration despite the passage of time, still enjoys great interest among researchers and engineers of industrial development. Due to the complexity of the biological processes underlying the basis of operation, many aspects of the action are not sufficiently well understood and therefore continue to be the subject of research combining different fields of science. Moreover, due to the possibility of aggregating biofilters with other devices such as UV and ozone radiation generators and using them as generators of electric current, new possibilities open up for it. The presented review of literature data is an attempt to draw attention to this research topic, which still poses new challenges.

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Abstract

The study presents a description of both the main problems of biofiltration as well as the new research directions. Discussion of the first subject covered the area of biofiltration applied in purification of exhaust gases. The method traditionally used for the purification of waste gases from biological processes is also suitable for the treatment of hot and dry air, contaminated with substances of high toxic concentrations. According to the literature reports, hydrocarbons belonging to all groups: compounds containing oxygen in the molecule such as aldehydes, ketones and esters, compounds containing nitrogen and sulphur in the molecule like amines, thiols or organic sulphides can all be filtered out. Chlorinated hydrocarbons and some inorganic compounds like ammonia and hydrogen sulphide can also be removed. All these substances can be present individually or in multicomponent mixtures.

The biofilters have been divided into conventional ones provided with a wet bed and the ones fitted with a biotrickling bed. A set of information on the materials used to compose a bed with a division into natural and synthetic has been given. The division of natural beds has been described as biodegradable, like peat, compost, wood chips and non-biodegradable as volcanic rocks. Among the synthetic beds mention are the ones made of mineral types of expanded clay aggregates and other minerals, as well as synthetic organic plastics, for example polyurethane foams.

Factors influencing the biofiltration process, such as gas flow rate, concentration of pollutants, their type and properties, temperature, humidity of gases and sediments, structure a bed, oxygen availability, salinity and pH of the bed, as well as the availability of nutrients not found in treated gases, were presented in the paper.

An extensive chapter was devoted to the microorganisms colonizing the bed of biofilter, which are responsible for the decomposition of filtered out pollutants. They can be introduced to the biofilter as microorganisms that naturally inhabit given building material or placed on a bed in the form of a vaccine. A consortium of microorganisms, formed during the start-up of a biofilter (adaptation), composed of bacteria and fungi, undergoes constant changes caused by the influx of new microorganisms along with purified air and the influence of environmental factors. These changes can be both quantitative and qualitative, manifested by the occurrence of genetic mutations. The microorganisms that colonize the bed belong to many species, such as *Pseudomonas, Pseudoxanthomonas, Xanthomonadales, Ralstonia, Mycobacterium, Exophiala i Candidia*. They metabolize environmental pollutants. This most often takes place during the catabolic process initiated by enzyme-assisted oxygen attack per molecule. As a result, appropriate alcohols are first formed, which than undergo successive transformations to aldehydes, fatty acids and further down to water and CO_2.

The chapter devoted to additives improving the bioavailability of pollutants such as methanol, silicone oils and surfactants, was included in the paper. New products in the field of construction solutions and hybrid systems were explained. Solutions such as rotary biofilters and cylindrical beds aim to reduce problems with even gas flow and excessive flow resistance. Among the hybrid systems, pre-filter solutions with active carbon and a UV pre-treatment module were presented. The idea of a biofilter combining the removal of pollutants with the generation of electric current in microbial fuel cells is also presented.

Keywords:
biofiltration, air biofiltration, biofiltration of air pollutants,
biofiltration – development trends

Biofiltracja zanieczyszczonego powietrza – stan aktualny, trendy rozwojowe

Streszczenie

W opracowaniu przedstawiono opis zarówno podstawowych zagadnień biofiltracji jak i nowych kierunków badawczych. Omawiając pierwsze z zagadnień zakreślono obszar zastosowań biofiltracji w oczyszczaniu gazów odlotowych. Metoda tradycyjnie przydatna do oczyszczania gazów odlotowych z procesów biologicznych nadaje się również do obróbki powietrza gorącego i suchego oraz zanieczyszczonego substancjami o wysokich toksycznych stężeniach. Zgodnie z doniesieniami literaturowymi odfiltrowywane mogą być

węglowodory przynależne do wszystkich grup, związki zawierające tlen w cząsteczce jak aldehydy, ketony i estry, związki zawierające azot i siarkę w cząsteczce jak aminy, tiole czy siarczki organiczne. Usuwane są także chlorowcopochodne węglowodorów oraz niektóre związki nieorganiczne jak amoniak i siarkowodór. Wszystkie wymienione substancje mogą występować pojedynczo oraz w wieloskładnikowych mieszaninach.

Podzielono biofiltry na klasyczne zaopatrzone w złoże utrzymywane w stanie wilgotnym oraz te ze złożem przepłukiwanym. Podano zbiór informacji o materiałach wykorzystywanych do komponowania złóż z podziałem na naturalne i syntetyczne. Podział naturalnych uściślono na biodegradowalne jak torf, komposty, zrębki drewna i naturalne nie biodegradowalne jak skały wulkaniczne. Wśród syntetycznych wymieniono mineralne typu poryzowane glinki i inne minerały oraz syntetyczne organiczne jak tworzywa sztuczne, przykładowo pianki poliuretanowe.

Zaprezentowano czynniki wpływające na bieg biofiltracji takie jak natężenie przepływu gazów, stężenie zanieczyszczeń, ich rodzaj i właściwości, temperatura, wilgotność gazów i złoża, tekstura złoża, dostępność tlenu, zasolenie i pH złoża, a także dostępność składników pokarmowych nie występujących w oczyszczanych gazach.

Obszerny rozdział poświęcono mikroorganizmom zasiedlającym złoża biofiltrów odpowiedzialnym za rozkład odfiltrowywanych zanieczyszczeń. Mogą być one wprowadzane do biofiltra jako mikroorganizmy naturalnie zasiedlające dany materiał budulcowy złoża lub wprowadzane na złoże w formie szczepionki. Uformowane w okresie rozruchu biofiltra (adaptacji) konsorcjum mikroorganizmów złożone z bakterii i grzybów ulega nieustannym zmianom wywoływanym napływem nowych mikroorganizmów wraz z oczyszczanym powietrzem oraz wpływem czynników środowiskowych. Zmiany te mogą mieć charakter zarówno ilościowy jak i jakościowy przejawiający się występowaniem mutacji genetycznych. Mikroorganizmy zasiedlające złoża należą do wielu gatunków takich jak np. *Pseudomonas, Pseudoxanthomonas, Xanthomonadales, Ralstonia, Mycobacterium, Exophiala i Candidia.* Metabolizują one zanieczyszczenia środowiska. Najczęściej ma to miejsce w procesie katabolicznym zapoczątkowanym wspomaganym enzymami atakiem tlenu na cząsteczkę. W efekcie najpierw powstają odpowiednie alkohole ulegające kolejno zachodzącym przemianom do aldehydów, kwasów tłuszczowych i dalej aż do wody i CO_2.

Zawarto dział poświęcony dodatkom poprawiającym biodostępność zanieczyszczeń takim jak metanol, oleje silikonowe czy surfaktanty. Omówiono nowości w zakresie rozwiązań konstrukcyjnych oraz układy hybrydowe. Rozwiązania takie jak biofiltry obrotowe i ze złożem cylindrycznym mają ograniczać problemy z równomiernym przepływem gazów i nadmiernymi oporami przepływu. Wśród układów hybrydowych zaprezentowano rozwiązania z przedfiltrem z węglem aktywnym oraz modułem wstępnej obróbki promieniami UV. Przedstawiono też ideę biofiltra łączącego usuwanie zanieczyszczeń z generacją prądu elektrycznego w mikrobiologicznych ogniwach paliwowych.

Słowa kluczowe:
biofiltracja, biofiltracja powietrza, biofiltracja zanieczyszczeń powietrza,
biofiltracja – trendy rozwojowe