Biodegradation 4: 283–301, 1993.

Biotechniques for air pollution control

Johan W. van Groenestijn & Paul G.M. Hesselink
Department of Environmental Biotechnology, TNO Institute of Environmental Sciences, P.O. Box 6011, NL–2600 JA Delft, The Netherlands

Received 3 December 1992; accepted in revised form 11 October 1993

Key words: air pollution, biofiltration, bioremediation, bioscrubbing, off-gas treatment

Abstract

This paper gives an overview of present biological techniques for the treatment of off-gases and the techniques that are being developed at the moment. The characteristics, advantages, disadvantages, costs and application area are discussed and compared. Biological off-gas treatment is based on the absorption of volatile contaminants in an aqueous phase or biofilm followed by oxidation by the action of microorganisms. Biofilters, bioscrubbers and biotrickling filters are used for elimination of odour and bioconvertable volatile organic and inorganic compounds and are enjoying increasing popularity. This popularity is a result of the low investment and operational costs involved compared to physico-chemical techniques and the elimination efficiencies that can be obtained. The operational envelop is still extending to higher concentrations and gas flow rates (exceeding 200,000 $m^3\ h^{-1}$) and a broader spectrum of degradable compounds. Research and development on the use of membranes and the addition of activated carbon or a second liquid phase to the biological systems may lead to a more efficient elimination of hydrophobic compounds and buffering of fluctuating loads. Shorter adaptation periods can be obtained by inoculation with specialized microorganisms. Improved design and operation are made possible by the growing insights in the kinetics and microbiology and supported by the development of models describing biological off-gas treatment. In conclusion, biotechniques are efficient and cost effective in treating off-gases with concentrations of biodegradable contaminants up to 1–5 g/m^3. They could play a justified and important role in air pollution control in the coming years.

Abbreviations: VOC – volatile organic compound, NO_x – gaseous oxides of nitrogen

Introduction

Most of our industrial and agricultural processes, transport functions and energy production systems generate gaseous emissions often of a polluting nature. In addition to local effects including odour nuisance, health impacts, crop damage and smog formation, transboundary problems have been recognized. These encompass depletion of stratospheric ozone, acid rain and the greenhouse effect. Public concern about this air pollution is rapidly growing. In many countries environment protection programmes are under way to reduce these problems. These programmes are based on emission prevention as well as on off-gas treatment, using emission guidelines as an important political tool. In addition, inventories are carried out to generate data on quantity and nature of the atmospheric emissions, sometimes with unexpected results. For instance, a recent inventory indicated that ethanol and hexane account for 90% of the emissions of VOCs (volatile organic compounds) by the EC food and drink industry (Swannell et al. 1991).

To meet the emission standards layed down in guidelines, various techniques for off-gas treatment have been or are being applied and developed. Amongst these are physico-chemical methods including separation with gas cyclones, adsorption on activated carbon, scrubbing, incineration, catalytic oxidation, (electro)filtration, dry-chemical treatment, selective catalytic reduction and biological methods such

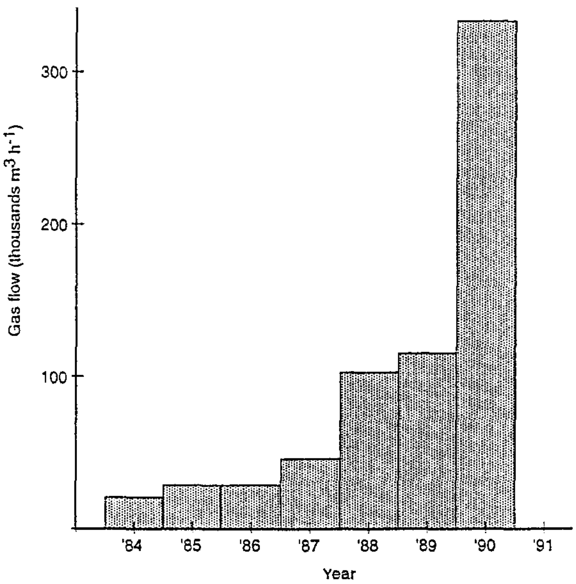

Fig. 1. Total gas flow treated with biofilters sold per year by two main Dutch companies (adapted from Dragt 1992).

as biofiltration, bioscrubbing and biotrickling filtration. In the last decade, especially biological abatement technologies have attracted an increasing popularity because of low costs, operational simplicity and because they are intrinsically clean technologies. There is minimal requirement of energy and raw materials and minimal waste production. In particular, biofiltration has become an accepted and mature technique for air pollution control and with a lot of industrial confidence. This is demonstrated by the exponentially increased capacity of biofilters installed by two big Dutch biofiltration companies resulting in 330,000 m^3 h^{-1} off-gas treated in 1990 (Fig. 1) (Dragt 1992). From the late 1970s most of the development work on biological off-gas treatment has been carried out in Germany and The Netherlands, in response to increasingly stringent national regulatory requirements. Nowadays, there is a growing interest in many other countries as well. However, worldwide dissemination of knowledge is hampered e.g. by a lack of descriptions written in the English language as a large part of recent results is published in German (Leson & Winer 1991).

In this paper biotechniques for off-gas treatment are described and current developments are reviewed. Emphasis is placed on recent results as presented at two conferences on this subject held in Köln (Germany) (VDI Berichte 735 1989) and Maastricht (The Netherlands) (Dragt & Van Ham 1992), supplemented with views and experiences of the authors.

Existing biotechniques

Biofiltration

Biofiltration is the oldest biotechnological method for removal of undesired off-gas components. Since the 1920s biofilters, often in form of soil beds, have been applied to remove odorous compounds e.g. H_2S from waste gases from wastewater treatment plants (Bach 1923; Leson & Winer 1991). Up to 1980 biofiltration has mainly been used to reduce odour in off-gases, but in the early 1980s the field of application was extended to the removal of many other volatile compounds that are easily biodegraded.

In biofiltration the gas to be treated is forced through a bed packed with material on which microorganisms are attached as a biofilm (Fig. 2a). Biodegradable volatile compounds are absorbed by the bed material and the biofilm and subsequently biologically oxidized into less harmful substances like CO_2, H_2O, NO_3^- and SO_4^{2-}. Usually, the packing material is a mixture of a natural fibrous substance with a large specific surface area and a coarse fraction. The first substance is the active fraction that contains most of the microorganisms and nutrients. Widely used materials are compost and peat. The coarse fraction serves as support material, prevents high pressure drops in the filter and may consist of inert materials like polystyrene or lava particles, or partially active natural material like wood bark, wood chips and heather (Roos & Fischer 1989; Ottengraf & Diks 1992). Many mixtures have been tested to develop optimal filter materials with high activities and a low flow resistance. For instance, VAMfil<trade> is a mixture of sieved compost (4–6 mm fraction and >10 mm fraction in a 1:1 mixture) mixed with wood bark (Don & Feenstra 1983; Don 1986). The specific gas/liquid surface area in biofilters ranges from 300 to 1000 m^2 m^{-3} (Ottengraf & Diks 1992).

Bioscrubbers

The use of scrubbers in off-gas treatment is well known: the gas is contacted generally with water in a spraying tower with inert packing, resulting in absorption of off-gas components in the water phase. The water with the dissolved target compounds is subse-

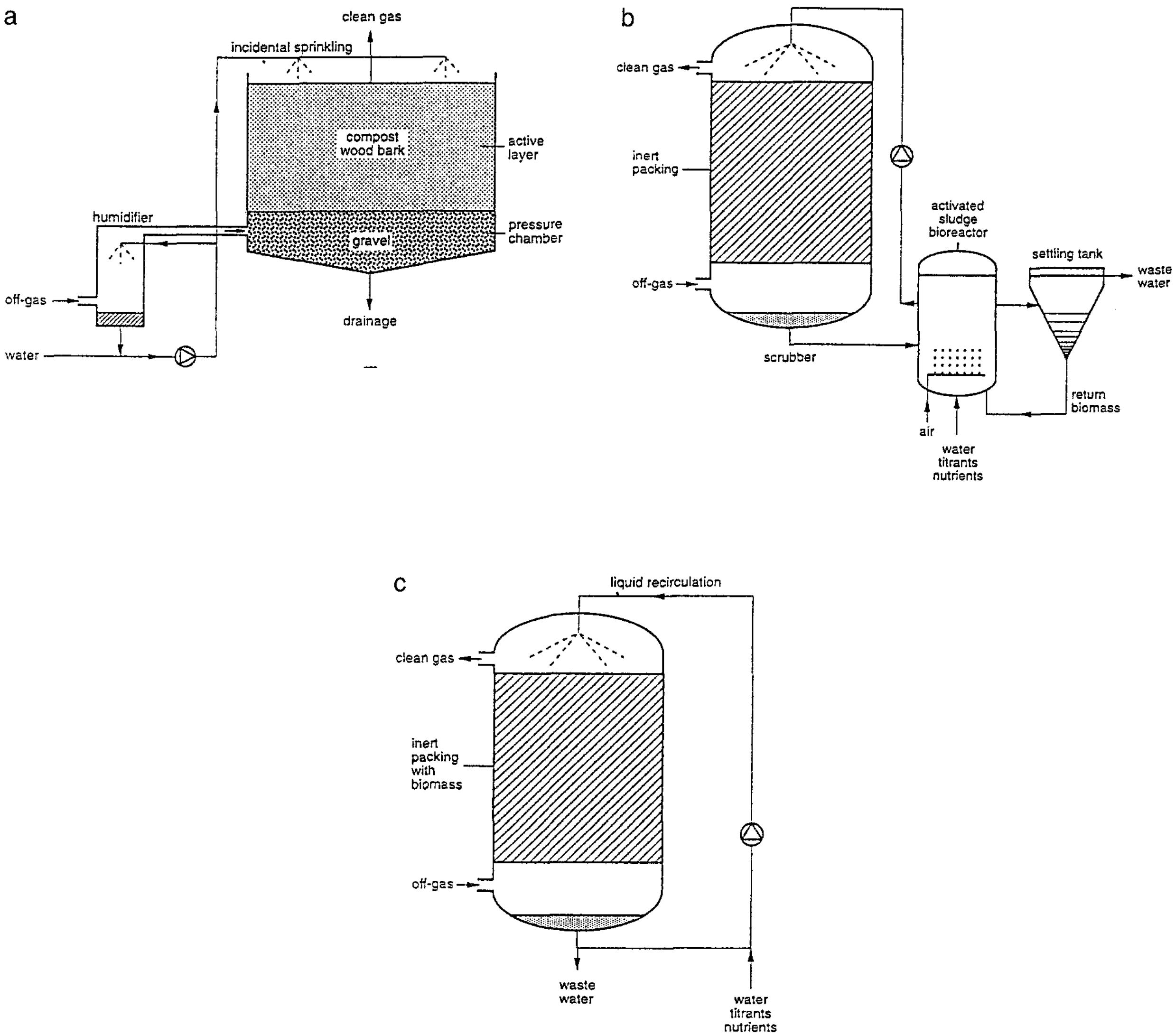

Fig. 2. Apparates for biological off-gas treatment. (a) biofilter (b) bioscrubber (c) biotrickling filter.

quently treated and reused or discharged. In case of bioscrubbing treatment takes place by biological degradation of the compounds. Thus, a bioscrubber consists of a scrubber and a bioreactor with activated sludge (Fig. 2b). The aqueous phase (often with suspended microorganisms) is continuously recirculated over the two separate units. In contrast to biofilters the liquid phase in bioscrubbers is mobile, which allows a better control of the reaction conditions. Nutrients, buffers and titrants can be added and the liquid can be refreshed and discharged in order to remove undesired products. In addition, temperature, pH and ionic strength can be monitored and controlled more easily. A drawback compared to biofilters is the lower specific gas/liquid surface area. This restricts the field of bioscrubber application to off-gas compounds with dimensionless Henry coefficients lower than 5–10 (Schippert 1989b) or even lower than 0.01 if one has to avoid high spray columns and large water flows (Kok 1992).

Biotrickling filters

Biotrickling filters can be regarded as an intermediate between biofilters and bioscrubbers. In biotrickling filters the off-gas is forced through a packed bed with inert material covered with an active biofilm. Like in bioscrubbers liquid is sprayed on the packed bed and continuously recirculated (Fig. 2c), which makes control of the reaction conditions easy. In contrast to bioscrubbers, absorption and biodegradation of the target compounds are combined in one column. A separate bioreactor for regeneration is not necessary, unless different reaction conditions are needed for conversion of intermediates or other off-gas components. Biotrickling filters have a lower specific surface area (100–300 $m^2\ m^{-3}$) than biofilters (Ottengraf 1987), which makes them unfit for treatment of poorly water-soluble compounds.

In Table 1 the advantages and disadvantages of the three described techniques are summarized. In compost production plants, sewage plants and in agriculture there is a preference for biofilters and biotrickling filters, while biofilters and bioscrubbers are preferred in industry (Ottengraf 1987).

Microbiological and operational aspects

Literature on microbiological and operational aspects of biological off-gas treatment is sparse yet, but some statements can be made by experience, by reference to similar areas of microbiology or by informed speculation.

Types of microorganisms and inoculation

All three biotechniques described are open systems. That is, there is a constant influx and outflow of gas, water and microorganisms. Therefore these techniques are dependent on environmental influences and contain mixed populations sensitive to changes. The populations in bioscrubbers and biotrickling filters are submerged cultures either suspended or largely immobilized, respectively. Such systems are abundantly described in literature on bioreactors and/or wastewater treatment (Van Gils 1964; Adamse et al. 1984; Diks 1992) and will not be discussed in detail in this review. However, they are mainly regarded as black boxes and are only poorly understood with respect to the dynamics, interactions and metabolism within the microbial populations. Biofilters contain immobilized biomass and can be regarded as solid state fermenters in a rather porous set up and with quite different microbiology. The ensuing discussion will concentrate on the microbiology of biofilters.

Most of the microorganisms found in biofilter materials are bacteria. Depending on the composition of the off-gas and physico-chemical conditions in the filter, different mixed populations may develop (Cox et al. 1993c). Rieneck (1992) found that most of the bacteria are coryneforms and endospore formers (e.g. bacilli) and occasionally pseudomonads. Actinomycetes are mainly represented by *Streptomyces* spp.. Yeasts and fungi are less abundant in biofilters. Most of the fungi belong to the *Mucorales* (*Mortierella* and *Rhizopus*) and *Deuteromycetes* (*Penicillium, Aspergillus, Cladosporium, Fusarium, Trichoderma, Alternaria* and *Botrytis*). According to Pearson (1992) the total bacterial count in biofilters packed with heather ranges between 5×10^7 and 3×10^{10} per g heather (dry weight). In addition moulds and yeasts are present in the range of 10^6–10^7 per g heather. The occurence of microaerophilic and anaerobic microorganisms in biofilters has never been published, but is nevertheless expected in oxygen depleted parts of thick biofilms.

Generally, it can be expected that the microbial population is in a pseudo steady state (constant biomass weight but not of constant composition and including turn over of cell material) after the adaptation period. This implies that there are no significant net increases or decreases in numbers of microorganisms which are in or close to the stationary phase with respect to their metabolism. As all biosystems, a newly installed biofilter will adapt itself with respect to its microbial ecology and physiological conditions to its environment and nutrient supply before efficient biodegradation will take place (Slater & Godwin 1980; Kluy & Reddy 1984; Cox et al. 1993c).

Although a wide variety of microorganisms is present in packing materials like compost, in many cases a faster start up can be achieved by inoculation with either specialized or non-specialized microorganisms. The following inoculants are generally used:

Activated sludge
If the filter is to be used to treat easily biodegradable compounds, activated sludge from wastewater treatment plants may serve as a source of microorganisms. The sludge should be poured on or mixed with the packing material.

Material from adapted biofilters
Material from biofilters which already eliminate poorly degradable or xenobiotic compounds can be mixed

Table 1. Characteristics, application area, advantages and disadvantages of basic biotechniques for off-gass treatment (adapted from Kok 1992).

Biofiltration	
Characteristics	**Advantages**
Immobilized biomass	* High gas/liquid surface area
Immobile water phase	* Easy operation and start-up
Single reactor	* Low operation costs
Application area	**Disadvantages**
Concentration target compounds < 1.0 g m^{-3}	* Poor control of reaction conditions
Henry coefficient < 10	* Slow adaptation to fluctuating concentrations in gas
	* Large area required
Bioscrubbing	
Characteristics	**Advantages**
Suspended biomass mostly	* Better control of reaction conditions (pH, nutrients)
Mobile water phase	* Possibilities to avoid accumulation of products
Two reactors	* Compact equipment
Application area	* Low pressure drop
Concentration target compounds < 5 g m^{-3}	**Disadvantages**
* Henry coefficient < 0.01	* Low surface area for mass transfer
	* Wash out of slow growing microorganisms
	* Stagnation periods of a few days detrimental
	* Disposal of excess sludge
	* Complicated start-up procedure
	* Extra air supply needed at high degradation rates
	* High investment, maintenance and operational costs
Biotrickling filtration	
Characteristics	**Advantages**
Immobilized biomass	* Comparable to bioscrubbing
Mobile water phase	* Better retention of slow growing microorganisms
Single reactor	* Single reactor
Application area	**Disadvantages**
* Concentration target compounds < 0.5 g m^{-3}	* Low surface area for mass transfer
Henry coefficient < 1	* Disposal of excess sludge
	* Complicated start-up procedure
	* Higher operational costs

with the packing material from the new filter. In this way the old material serves as an inoculum.

Pure cultures or consortia of specialized microorganisms

Some compounds, in particular xenobiotics, are only degraded by a limited number of microorganisms. Development of specialized consortia in filters inoculated with activated sludge may take months (Cho et al. 1992). To shorten this lag phase, pure or mixed cultures of specialized microorganisms can be added. These cultures may be obtained from culture collections or can be isolated from laboratory enrichment cultures. An additional advantage of defined cultures is the knowledge on their properties. The relation between activity and physiological conditions (pH, temperature, substrate concentration) can be determined and the reactions catalyzed by the organism(s) can be revealed. Excretion of possible intermediate and final products can be determined as a function of environmental conditions, and biodegradation can thus be optimized.

Substrates

Compounds that can be degraded in all three techniques include alkanes, aldehydes, alcohols, ketones, carboxylic acids, esters, ethers, alkenes, many aromatic compounds and other cyclic compounds (e.g. terpenes), heterocyclic compounds, epoxides, and organic compounds containing - NH_2 (like amines), - SH (like mercaptanes) and halogens (Van Ginkel et al. 1987; Henson et al. 1989; Maier 1989; Sabo 1989; Wolff 1989; Swannell et al. 1991; Cho et al. 1992; Demiriz 1992; Demmers 1992; Diks 1992; Joziasse & Wiering 1992; Mackowiak 1992; Cox et al. 1993b). Further, compounds like CS_2 and dimethylsulphide can be converted into mineral products as well as many odorous organic compounds. Under appropriate conditions these compounds are completely oxidized yielding CO_2 and H_2O as main products. Some volatile inorganic compounds can be oxidized in biofilters as well. Conversion of H_2S into sulphate and NH_3 into nitrite or nitrate are two important practical examples.

Factors affecting elimination rates

All biotechniques are a combination of the two unit processes mass transfer (absorption from the gas) and biodegradation. Therefore, success is not solely dependent on the biodegradability of the compound but also on the gas/liquid interfacial mass transfer rates and the (aqueous) diffusion coefficients of the substrate and oxygen. Gas-liquid mass transfer can be described by a general formula (Van 't Riet & Tramper 1991) like

$$F'' = K_l a(C^* - C), \qquad \text{in which } C^* = C_g/H$$

Symbols used:

- F'': mass transfer rate (mol m^{-3} s^{-1})
- K_l: overall interfacial mass transfer coefficient (m s^{-1})
- a: interfacial area per unit of volume (m^2 m^{-3})
- C^* concentration in the liquid phase in equilibrium with the gas phase (mol m^{-3})
- C: concentration in the liquid phase (mol m^{-3})
- C_g: concentration in the gas phase (mol m^{-3})
- H: Henry coefficient (–).

Interfacial area (a) depends on the structure of the support material, e.g. particle size and pore area, while K_l is dependent of flow characteristics near the interface, diffusion, etc.. Thus, mass transfer is dependent on reactor set-up and chemical and physical characteristics of the off-gas and the target compounds.

The absorption rate depends on the Henry coefficient. Poorly soluble compounds with Henry coefficients higher than 10 are considered unfit for treatment in biofilters because of the low interfacial mass transfer rate (Kok 1992).

From a biological point of view, the biodegradation rate of a compound in biofilters depends on the type of microorganisms involved and the amount of biomass present, the micro-environment of the microorganisms, the cellular regulatory conditions and metabolic regulation. These factors are discussed in more detail below.

1. Biomass development

After inoculation, the microorganisms, which are able to grow on the gaseous organic carbon compounds, will accumulate in the biofilms of the filter. Besides the carbon compounds for biomass and energy production, oxygen is needed as an electron acceptor. Generally, oxygen is continuously supplied by the off gas stream. Other elements needed to produce biomass are slowly released by biofilter packing materials. It can be expected that these components are turned over in the biofilm, including elements from dead cells being reused by growing cells. Also a slow wash out and efflux with the drainage water may occur. Growth of microorganisms which need growth factors depends on the release of these factors by dead cells.

Growth will generally continue until one of the elements other than C, H and O in the biofilm is depleted. At that time, the biomass reaches a stationary phase in which carbon compounds are only used for the maintenance of the cells and little replacement of dead cells. A stationary situation will be reached in the order of a few weeks and may continue for years (own observation). As the substrate consumption rate of stationary cells is usually lower than that of growing cells a small decrease in filter performance can be expected. Therefore, the conversion rates studied and evaluated in the laboratory should be based on stationary cells rather than growing cells when predicting yields and efficiencies for practical applications.

As carbon sources are usually abundantly supplied in the off-gas, the amount of biomass in biofilters is often limited by the amount of mineral nutrients present (Don 1986). Addition of potassium- or calcium phosphate may increase the biofilm thickness. However, this may not always lead to higher volumetric activities because of diffusion limitation of carbon compounds or oxygen. In general: more biomass causes more pore clogging and therefore mass transfer limitations.

Although it has never been proven or studied, it can be expected that the processes in biofilters are influenced by microbial interactions like symbiosis, competition and inhibition, e.g. by antibiotic production. Competition will be especially important in case of treatment of mixtures of off-gas components. It can be expected that at the inlet side of the filter microorganisms with a broad substrate specificy will only convert the easily degradable compounds, while specialized organisms selected to degrade solely specific poorly degradable compounds will hardly be able to develop as they are excluded by competition with other organisms for oxygen, nutrients and area. The poorly degradable compounds will be converted only when some other compounds are totally removed. This may be the case deeper inside the filter or in a second separate filter.

2. The micro-environmental conditions
Temperature, pH, moisture content and concentration of salts are important next to dissolved oxygen, substrates and nutrients for cell turn over.

Operation of all biotechniques should preferrably be between 20 °C and 40 °C (Leson & Winer 1991). Cooling of off-gases, e.g. by humidifying, may be necessary as a pretreatment.

The pH of the aqueous phase should be between 6 and 9 (Leson & Winer 1991; Ottengraf & Diks 1992). If biofiltration leads to the accumulation of acids like HCl (during degradation of chlorinated compounds), nitric acid or sulphuric acid in the biofilm, measures should be taken to control the pH. Options are prior addition of a buffer, precipitation with alkaline (prior addition of $Ca(OH)_2$) or periodical washing and drainage. If the biotechnique is only used to oxidize H_2S by the action of acidophilic thiobacilli, lower pH's can be tolerated. A pH of 2.5–3.5 has been measured in biofilters which succesfully removed H_2S (Schelchshorn & Vink 1989). At low pH's fungi may overgrow the bacteria which may affect filter performance negatively or positively (Cox et al. 1993c).

The water content of compost biofilters should be higher than 40% w/w as a practicle rule of thumb (Ottengraf 1986). In fact the water activiy (A_w) is the real parameter one should measure. In biofilters with too low a moisture content fungi are expected to dominate the bacterial population. The effects of this on performance are unknown: probably a new lag time is introduced with temporary malfunctioning. Water contents of more than 60% should be avoided as it decreases the gas/liquid surface area and may lead to mass transfer problems in biofilters (Ottengraf 1986).

Microbial activity is influenced by accumulated high concentrations of inorganic salts as well as by depletion of ions. Thus, neutralization of acids produced in biofilters should not be carried out by adding caustic soda as it increases the ionic strenght in the aqueous biofilm, unless sprinkling and draining is applied. A decrease of moisture content will also increase the ionic strenght. According to Oude Luttighuis (1989) production of HCl resulting from degradation of chlorinated hydrocarbons can be coped with by buffering with $CaCO_3$ combined with incidental sprinkling and draining. As draining also causes a wash out of essential nutrients, this process should be carried out in a controlled way and not too frequently. Then, a biofilter for chlorinated hydrocarbons can work succesfully for several years.

3. Inhibition by high concentrations of substrates and products
The maximum substrate concentration in the bioreactor depends on the concentration in the gas phase and the Henry coefficient. Laboratory studies may be carried out to test the effect of substrate concentration on microbial activity.

As mentioned above biofilter performance can be affected by accumulation of inorganic products. The same can be caused by accumulation of intermediates or incompletely oxidized organic compounds. Laboratory studies can be carried out to reveal the reason for this incomplete oxidation and to suggest biofilter improvements. In some cases it is caused by oxygen limitation, in others by inhibition of specific reaction steps. An example of the latter effect is described by Engesser (1992). Although toluene and chlorobenzene are easily degradable as single compounds, problems may arise with mixtures of these compounds. The author reported inhibition of toluene degradation when chlorobenzene is degraded simultaneously by the same organism. This is caused by suicide inactivation of the enzyme metapyrocatechase in aromatics degradation by chlorosubstituted analogues.

Cellular regulatory conditions

Suboptimal elimination rates may be caused by a long lag phase, diauxie or catabolite repression. Lag phases may be a problem in case of starting up or intermittent loading, while diauxie may retard the degradation of a poorly degradable compound if a more attractive alternative substrate is also present (Harder & Dijkhuizen 1982).

Some poorly degradable compounds, e.g. several xenobiotics, are converted by enzymes belonging to another pathway that is only induced by an entirely different substrate. Addition of these cosubstrates will result in production of biomass with all relevant pathway, causing cometabolism of the xenobiotic. Without the addition of the cosubstrate no active biomass will develop and no xenobiotic will be removed. Examples are degradation of trichloroethylene by *Pseudomonas cepacia* G4, which needs phenol, toluene or tryptophan for growth and energy (Folsom et al. 1990), and the degradation of chlorinated methanes, ethanes and ethylenes by methylotrophic microorganisms which require cosubstates like methane as a source of carbon and energy (Henson et al. 1989). However, the use of methane as a growth substrate in biofilters will challenge the application in practice due to e.g. the explosion danger and mass transfer limitations.

Operation and construction

In order to create a suitable microenvironment for optimal biodegradation and adequate mass transfer the following aspects of operation and construction are important (Roos & Fischer 1989).

Preconditioning of the off-gas may be necessary for optimal operation. Removal of dust, fat and aerosols by filtration or scrubbing prevents clogging of the filter. Humidification to a relative humidity higher than 95% is necessary to prevent drying. Cooling should be applied in case of off-gas temperatures higher than 40 °C.

The height of the filter bed usually is between 0.5 and 1.5 m. Higher filter beds may suffer from a high flow resistance, while filters with a lower height are more subject to channeling, causing off-gas to pass through the biofilter virtually untreated. If space is not available for large biofilters a multiple story biofilter can be installed with separate inlet points at each floor. Open biofilters are subject to weather conditions like rain and temperature, causing unstable or suboptimal performance. Enclosed biofilters should be built in a container which makes maintenance, process control and continuous gas monitoring more easy.

The gas can be forced downflow or upflow through the filter. Upflow ventilation is used in open filters and can be organized more easily. However, downflow operation prevents drying out of the lower parts better (the sprinkler is at the top) and limits a discharge of VOCs dissolved in the drainage water (own observations).

Biofilter operation includes incidental sprinkling of water on the top of the filter to replenish evaporated water and addition of raw materials (nutrients and titrants) if necessary. The frequency and needed amounts initially results from measurements on pH, water content, filter weight and performance and in a later stage on experience.

Measurement of biological activities in biofilters

The volumetric elimination capacity of filter material can be determined and studied by taking samples of the biofilter packing material and performing the following tests:

- The oxidation rate of single compounds by the filter material can be determined in a Sapromat, an apparatus in which microbial oxygen consumption can be measured in bottles with biofilter material.
- Alternatively, filter material can be suspended in a buffer containing the off-gas compound of interest after which the disappearance of the compound can be monitored using GC or HPLC.

The general microbiological condition in the filter can be determined by the following methods:

- Measuring the CO_2 production rate after addition of glucose to samples;
- Measuring the dehydrogenase activity e.g. via oxidation of added 2-(*p*-iodophenyl)–3-(*p*-nitrophenyl)–5-phenyl-tetrazolium chloride (Rieneck 1992);
- Qualitatively by determination of the amount of colony forming units in the filter material (indicative of microorganisms capable of degrading specific compounds in the off-gas). The method is less suitable for quantitative analyses, as it is difficult to obtain a suspension of free single cells.

Emission of microorganisms from biofilters

Food, fermentation and pharmaceutical industries need a production environment in which low numbers of microorganisms are present. Special attention should be given to microbe emission from biofilters at their sites. Biofilters emit microorganisms but also capture them from off-gases. Reported emissions are 10^3–10^4 CFU per m^3 gas treated, which concentrations are comparable to those in indoor air (Konings & Ottengraf 1988; Ottengraf & Diks 1992).

Modelling

In the last decade theoretical models have been developed to describe biological and physical processes in biofilters and biotrickling filters. The models aim to predict elimination capacity and efficiency as a function of reactor design, properties of the target compound and microbiological parameters, and can be used for dimensioning and designing of the filters. In general, the models are based on integration of mass transfer and biodegradation processes, assuming Monod or Michaelis-Menten kinetics.

One of the first models for biofilters was presented by Ottengraf and Van den Oever (1983) (Ottengraf 1986). Their model describes diffusion of organic contaminants from the gas phase to the aqueous biofilm and biological oxidation in the biofilm. Microkinetics (Michaelis-Menten kinetics) were used to model the macrokinetics of the biofiltration process. This implies the establishment of concentration gradients of substrates and products, resulting from internal mass transport by diffusion and substrate depletion by reaction. Other important assumptions were: transport of nutrients in the biofilm by diffusion, the thickness of the biofilm is smaller than the diameter of the coated particles, plug flow of the gas, and a negligible interfacial resistance in the gas phase. Then the elimination efficiency depends on packing height, specific gas-liquid surface area, effective diffusion coefficient and Henry coefficient of the pollutant, superficial gas velocity, biofilm thickness, biomass concentration, maximum reaction rate, Michaelis-Menten constant and concentration of the contaminant in the influent gas. Different expressions were derived for zero-order kinetics, specified for reaction and diffusion limited processes, and first-order reaction kinetics. The Thiele number, which reflects the ratio of the maximum rate of degradation and the maximum rate of diffusion in the biofilm, was used to differentiate between reaction and diffusion limitation. If this number had a value higher than 1.4 the process was expected to be diffusion limited.

In experiments with gases containing low concentrations of toluene the predicted diffusion limitation was verified experimentally and the measured elimination efficiencies were in good agreement with the theoretical values (Ottengraf & Van den Oever 1983).

Furthermore, it was established that in many cases the elimination of VOCs within the filter bed follows zero-order reaction kinetics down to very low concentrations of substrate. However, at low gas phase concentration levels or low water solubility of the compounds concerned, the elimination rate may become diffusion-controlled in the biolayer (Ottengraf 1987).

Biotrickling filters with biocatalysts (i.e. microorganisms) immobilized on grains of activated carbon were modelled by Kirchner et al. (1987). In experiments with 5–40 ppm of organic solvents the mass transfer through the biofilm around the grains seemed to be rate determining. This implies that the elimination efficiency is solely dependent on the gas-liquid mass transfer coefficient, specific surface area, degree of wetting, liquid flow rate, area of reactor cross section and reactor height.

Another model for biotrickling filters was presented by Wolff (1992) in which the elimination efficiency is a function of the maximum reaction rate, concentration in the water phase, height of the filter, Michaelis-Menten constant, Henry coefficient, superficial gas velocity, specific surface area and concentration in the influent gas. A similar model for biotrickling filters and biofilters was described by Windsperger (1992).

A specific model for removal of dichloromethane from waste gases in biotrickling filters was developed by Diks & Ottengraf (1991). Experimental verification showed that the filter performance could be well predicted. Experimental and theoretical results revealed that the relative flow direction (co/counter current) of the mobile phases did not significantly affect the filter performance. Moreover, it was found that the gas-liquid mass-transfer resistance in the biotrickling filter applied was negligible, which suggests the biological process inside the biofilm is the rate limiting step.

Schippert (1989b) developed a specialized model for the elimination of poorly water-soluble VOCs in bioscrubbers with added organic solvents as second liquid phase.

The use of these models for prediction of the elimination efficiency before any experiment has been carried out is limited. The user has to estimate or assume the values for specific surface area, biofilm thickness and biomass concentration. This will generally be difficult, particularly for biofilters. More realistic is the use of models to predict the effect of changes in filter operation and dimensions and off-gas composition, e.g. in case of scaling up pilot plants or fluctuations in off-gases.

Recent developments

Activated carbon

Kok (1992) proposed the application of suspended activated carbon in bioscrubbers to improve mass transfer of hydrophobic volatile compounds in the scrubber and to buffer fluctuations in the supply of contaminants. This should result in suitable biological treatment techniques for off-gases containing contaminants with Henry coefficients higher than 0.01 at concentrations of 0.5–5 g m^{-3}. These gases might thus be treatable in bioscrubbers with added granular activated carbon on which microorganisms are attached.

Ottengraf et al. (1986) already suggested the application of activated carbon filters as a buffer in combination with biofilters for plants operating discontinuously. The activated carbon filter should be placed before the biofilter. For the same purpose, various adsorbents like silica gel, Al_2O_3 and several types of activated carbon were tested by Weber & Hartmans (1992). They concluded that selection of the most suitable type of adsorbent for a specific application depends on the nature of the contaminant and on the magnitude of the concentration fluctuations in the waste gas. In experiments with fluctuating toluene concentrations (0–1500 mg m^{-3} gas) in a 24 hours cycle and a volumetric load of the activated carbon filter of 1000 m^3 gas m^{-3} h^{-1} they demonstrated that a filter packed with Norit RB activated carbon was able to limit the fluctuations to values between 200 and 800 mg m^{-3}.

Alternatively, activated carbon can be mixed with compost in biofilters. In some cases an increase of the elimination capacity can be obtained by this method. Demonstrations with butanol were more succesful than with xylene in this respect (Eitner 1989).

Two-liquid-phase systems

Poppe (1992) demonstrated the advantages of adding water-immiscible organic solvents to the liquid phase of bioscrubbers for the elimination of hydrophobic VOCs. By adding organic solvents with high boiling points in a range of 10%–30% of the total volume, 100 to 1000 times larger amounts of hydrophobic target compounds were absorbed in the scrubber part. In the bioreactor the target compounds were transferred from the organic phase to the water phase driven by the low concentration in the water phase caused by biological degradation. This new technique was demonstrated by treatment of a mixture of 13 volatile compounds in air by a two stage bioscrubber. The first bioscrubber was conventional, while the second contained the organic solvent. Each stage included an aerobic biological regeneration reactor. In the first stage mainly hydrophilic compounds such as ethylacetate, butylacetate and aceton were removed, while hydrophobic compounds passed completely. They were removed in the second stage only. Positive results were obtained with toluene, ethylbenzene and xylene. By this treatment, the xylene concentration decreased from 16 mg to 2 mg m^{-3} gas.

A suitable bioreactor for a two liquid phase system is being studied by Cesário and coworkers (1992). They propose a combination of a spray tower and a liquid-impelled loop reactor. In this system a water-immiscible organic liquid with a high solvent capacity for the pollutant is recycled between absorber and bioreactor. The latter is designed as a liquid-impelled loop reactor, a relatively new type of liquid/liquid contactor which contains the culture medium and the cells (Tramper et al. 1987). This reactor consists of a riser and a downcomer. The organic solvent is introduced at the bottom of the riser and causes the low density water/solvent mixture to rise. At the top of the reactor the two phases are separated. The organic phase is recirculated via a spray scrubber to the bottom of the riser, while the aqueous phase is recirculated via the downcomer. In this reactor transfer of the pollutant from the organic liquid to the aqueous phase and subsequent biological degradation occur. According to Schippert (1989b) and Cesário et al. (1992) the organic solvent has to meet the following conditions:

- high solvent capacity for organic compounds,
- immiscible with water,
- low solubility in water,
- inert to biodegradation,
- not toxic for biocatalyst,
- low vapour pressure,
- relatively low viscosity,
- density different from the density of water,
- odourless,
- favourable price,

depending on the waste volume to be treated, physico-chemical characteristics and concentration of the pollutant in the waste gas and desired removal efficiency. Di-*n*-octylphtalate, di-*n*-nonylphtalate and polydimethyl-siloxane are recommended by Schippert (1989b), while Cesário et al. (1992) focusses on Silicon oil DC 200 (polydimethyl-siloxane) in experiments with hexane as a target pollutant.

Membranes

A third new biotechnique for treatment of hydrophobic volatile compounds is the use of membranes integrated with bioreactors. Two different approaches have been reported: the use of semipermeable hydrophobic membranes and the use of microporous membranes. Both membranes keep the gas phase and liquid phase with microorganisms separated and allow transfer of the volatile target compounds between the two phases.

Fischer (1992) tested dimethylsiliconrubber as membrane material which has a high permeability for aromatic compounds. The membrane bioreactor was able to eliminate styrene at a rate of 20 g m^{-3} reactor volume h^{-1} and toluene at 40 g m^{-3} h^{-1}, while the conversion capacity of biofilters for aromatic compounds ranges mostly around 20 g m^{-3} h^{-1}. However, in case of a mixture of hydrophilic and hydrophobic compounds only the latter category was eliminated adequately. In experiments with a styrene/methanol mixture methanol was hardly removed by the reactor. The author concluded that mixtures of hydrophilic and hydrophobic compounds should be treated by a combination of a biofilter and a membrane bioreactor, as these systems work in a complimentary manner.

A different approach is the use of microporous membranes which have very large (specific) surface areas. Hartmans et al. (1992) tested different hydrophobic membrane materials. Polypropylene membranes were selected for further studies as no growth of bacteria through the membrane could be observed and because of the high mass transfer rates attained. The microorganisms were located in biofilms at the liquid side of the membrane or in suspension. Toluene and dichloromethane were removed from air with a high efficiency. They calculated that for a 82% removal of dichloromethane starting at 100 mg m^{-3} off-gas the membrane reactor should have a volume of 0.35 m^3, whereas the same results could be obtained with a 1 m^3 biotrickling filter.

Parallels can be drawn with a new physico-chemical off-gas treatment technique based on hydrophobic microporous hollow fibre membranes. The volatile contaminants are absorbed in the liquid phase driven by a low concentration caused by a chemical reaction (Ter Meulen 1991). This technique is called transmembrane-chemosorption (TMCS). Demonstration plants have been set up by TNO for removal of SO_2 from off-gases and new applications using biological reactions are being developed (transmembrane-biodegradation: TMB). So far, 99% ammonia removal was realized by conversion into N_2 starting with 28 mg NH_3/m^3 gas. In these new applications the driving force for absorption of the contaminant is generated by biodegradation which can take place in biofilms attached to the membranes or in flowing cell suspensions in a membrane bioreactor or in a membrane module/ bioreactor loop (Fig. 3).

Fungi

In biofilters the aerial hyphae of fungi form a very large specific surface area which is in direct contact with the air flowing through the filter. Thus, the pollutant is transferred directly to the cell surfaces without bulk phase transition problems. This may improve absorption of hydrophobic volatile compounds. Majcherczyk et al. (1990) did experiments with biofilters based on white-rot fungi growing on straw or other agricultural residues. When growing on straw, the fungus secretes oxidative enzymes that catalyze the degradation of lignin. These extracellular enzymes are very non-specific and are able to degrade many aromatic compounds as well. When testing this oxidative potential combined with the large biologically active surface area, the elimination of styrene, *alpha*-pinene and chlorophenols from air was demonstrated.

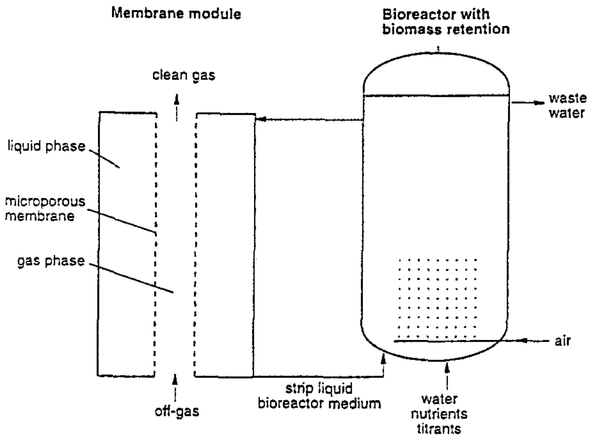

Fig. 3. Transmembrane-biodegradation by the use of separate units for absorption and biodegradation.

In our laboratory, styrene degrading fungi were introduced in biofilters packed with inert support material. Growth of the fungi was observed and the filters showed a high and constant activity, although the relative humidity of the off-gas was only 85% and humidification of the filter bed was only incidental. A 100% removal efficiency and an elimination capacity of at least 70 g styrene per m^3 filter per hour was found in filters with growing fungi, while a removal efficiency of 50% (at a load of 60 g m^{-3} h^{-1}) was observed when fungi in a stationary phase were used (Cox et al. 1993a). New experiments indicate a longterm conversion capacity of 120 g/m^3 · h. Scaling up is foreseen in the nearby future.

Specialized microorganisms

Knowledge of biodegradation of complex volatile compounds is accumulating. Metabolic pathways are revealed and new microbial strains are isolated that are able to degrade these compounds. Considerable progress has been made in the field of biological degradation of xenobiotics, in particular chlorinated organic compounds. For example degradation of xenobiotics by cometabolism has been described by many authors (Janssen et al. 1989), as well as the process of reductive dehalogenation of highly halogenated organic compounds that occur under anaerobic (methanogenic) conditions (Dolfing & Tiedje 1987; Holliger 1992). An ever increasing number of strains degrading an increasing number of xenobiotics can be found in culture collections, while specialized commercial firms have started to sell them. In addition, the adaptation of microorganisms to xenobiotics in natural environments has been studied, and the role of intercellular gene transfer in adaptation (by exchange of transposons encoding for parts of the catabolism of xenobiotics) has been indicated (Van der Meer et al. 1991; Van der Meer 1992). Several of these recently acquired scientific insights can be applied to biological off-gas treatment. Most applications reported so far deal with shortening the adaptation period in biological treatment and creating optimum conditions for degradation of specific compounds.

Kirchner et al. (1987) stated that long adaptation periods and low space velocities are important reasons for the lack of general acceptance of biotechniques for biological off-gas treatment in practice. Introduction of pure cultures may help to overcome these problems. The authors did experiments with monocultures like *Pseudomonas fluorescence* and *Rhodococcus* sp. immobilized on activated carbon in trickle bed reactors. They demonstrated that volumetric loads of 1500 m^3 air m^{-3} h^{-1} can be obtained at a conversion efficiency of 90% propionaldehyde or methylethylketone.

Cho et al. (1992) obtained an enhanced removal efficiency of malodorous gases in a pilot-scale biofilter inoculated with *Thiobacillus thioparus* DW44. This strain was isolated from a biofilter adapted to dimethyldisulfide and introduced in a peat biofilter to treat the exhaust gas from a night soil (= faeces) treatment plant. H_2S, methanethiol, dimethyl sulfide and dimethyl disulfide were efficiently removed (90–100%) during six months at a space velocity of 46 h^{-1}. No adaptation period was needed, which can be considered as a great improvement compared with uninoculated biofilters in which acclimation usually takes two weeks to six months.

Usually biofilters are started up by inoculation with activated sludge. A six times faster start up of biofiltration of volatile organic solvents can be achieved by inoculation with adapted microorganisms (Hübner and Saake 1989).

Succesful introduction of ethene degrading pure cultures of *Mycobacterium* E3 in biofilters was reported by Van Ginkel et al. (1987). A compost filter was used to eliminate the plant hormone ethene from air in storage buildings for crops and horticultural plants. Uninoculated filters showed activity only after weeks, while filters with introduced mycobacteria were immediately active. A gas residence time of 4 minutes was necessary to decrease the ethene concentration from 2–50 vpm to less than 1 vpm. The same strain was used for inoculation of biotrickling filters which contained polyurethane foam as support material (De Heyder et al. 1992). In this case start up took much more time, caused by a slow colonization and growth of the bacteria on the foam. After three weeks, 25% elimination of 122 ppm ethene was obtained at a gas residence time of 45 s.

The fate of an inoculum in biofilters was investigated by Fritsche and Lechner (1992). Bacterial strain S1, able to use 4-chloro-2-methyl phenol and 2,4-dichlorophenol as sources of carbon, and resistant against lincomycin and oxacillin, was introduced in a compost biofilter. At a volumetric load of 100 m^3 m^{-3} h^{-1} and an initial concentration of 20 mg total chlorophenols per m^3 air, 100% elimination of the two mentioned xenobiotics was observed. After three months operation a gradient of colony forming units (CFUs) (antibiotic resistant) per g filter material was measured, ranging from 0.6×10^8 at the top to 8.9×10^8 at the bottom of this up-flow reactor, correlating with the concentration gradient of chlorophenols. Total counts of CFUs carried out without antibiotics were 20% higher, both at the top and the bottom, indicating the presence of other microorganisms. The authors proved that amongst the nonresistant organisms species were present which were also able to degrade chlorophenols, and discussed the favourable conditions for gene transfer in biofilter biofilms.

Bronnenmeier & Menner (1992) screened bacteria which were tolerant to high concentrations of formaldehyde and were able to convert this compound in presence of methanol and ethylene glycol (no diauxie). Other required characteristics included a high conversion rate, rapid reactivation after feed intermissions and nonpathogenicy. Two pseudomonads, isolated from biofilters, were selected and introduced in a bioscrubber for the treatment of off-gas containing formaldehyde, methanol and ethylene glycol. The scrubber reached its maximum conversion capacity after two days. Weekend intermissions resulted in a 30–60% decrease of the activity as tested in liquid samples which was restored again after two days. However, no negative effect on the elimination efficiency was observed (89%–100%). Most of the biological activity was located on the submerged packing material in the bioreactor and only a small part in the recirculating medium. After 70 days of operation 70% of the microorganisms present in the bioreactor were pseudomonads.

Hyphomicrobium sp. GJ21, able to degrade dichloromethane was used for inoculating biotrickling filters (Diks & Ottengraf 1991; Diks 1992). As a result of attached growth biofilms were developed with a thickness of hundreds of μm. The elimination capacity for dichloromethane reached a value of 157 g m^{-3} filter h^{-1} in this system.

Not only prokaryotic microorganisms are investigated for use in biological off-gas treatment, growing interest can be observed for the largely hidden potential of eukaryotes to degrade xenobiotics and volatile organic compounds. Experiments with white rot fungi growing on chips of wood in biofilters indicated the conversion of styrene and aliphatic alcohols (Braun-Lülleman et al. 1992). Fungi and black yeasts converting styrene and related compounds have been tested in biofilters (Cox et al. 1993a, 1993b).

Practical application

Recently reported practical experiences

Many industrial practical experiences have been reported in the last four years (Van Groenestijn et al. 1993). Most of them involve full scale biofilters, while bioscrubbers and biotrickling filters seem to be less popular. A selection is presented in Table 2 in which capacities and efficiencies are evaluated.

Biofilters

Flow rates up to 200,000 m^3 h^{-1} can be succesfully treated by biofiltration and filter volumes exceeding 3000 m^3 are reported (Huber 1992). Both multi-story and one-story (or flat) filters are used, independent of the filter size. Volumetric loads between 100–200 m^3 m^{-3} h^{-1} are usual. Concentrations of target compounds are mostly in the hundreds of mg m^{-3}. Commonly used packing materials are tree bark, heather and mixtures of peat/heather, compost/wood bark, compost/polystyrene and peat/heather/pine branches. Elimination capacities (including pilot plants) are: 180 g ethylacetate m^{-3} filter h^{-1} (Nolte 1992), 200 g ethanol m^{-3} h^{-1} (Van Groenestijn et al. 1992), 9–50 g VOC-carbon m^{-3} h^{-1} (Hübner & Saake 1989), 8–13 g VOC-carbon m^{-3} h^{-1} (Mildenberger 1992) and 11 g styrene m^{-3} h^{-1} (Demiriz 1992), reconfirming the correlation between biodegradability and filter capacity.

Table 2. Summary of recent practical experiences with biological off-gas treatment in industry. In all examples full scale plants are involved, with the exception of those indicated by "p", which are pilot plants on site. For calculation of the volumetric load of bioscrubbers the sum of the volumes of the scrubber and the bioreactor is used.

Compound	Industry type	Elimination efficiency (%)	Flow rate ($m^3 h^{-1}$)	Volumetric load ($m^3 m^{-3} h^{-1}$)	Reference
			BIOFILTERS		
Odour	Animal rendering	94–99	214,000	66	Huber (1992)
Odour	Tabaco industry		180,000	109	Kersting (1992)
Odour	Vegetable oil	97	39,000	120	Eitner (1992)
Odour	Gelatine works	49–93	35,000	146	Kirchner (1990)
Odour	Cocoa roasting	>99	4,000	73	Hofmann (1989)
Odour	Wastewater treatm.	80–90	5,000	7	Mildenberger (1992)
VOCs	Storage tanks	90	2,000	8	Mildenberger (1992)
VOCs	Industrial waste-water treatment	70–90	65,000	31	Mildenberger (1992)
VOCs	Fish processing	95	6,300	105	Liebe (1989)
VOCs	Fish processing	85	10,300	184	Liebe (1989)
H_2S	Landfill gas	>99	300	17	Sabo (1989)
Alcohols	Foundry	>99	30,000	150	Maier (1989)
Aromatics	Foundry	80	40,000	120	Maier (1989)
Aromatics	Surface coating	85–90	1,500 (p)	79	Demiriz (1992)
Styrene	Resins processing	65	p	100	Demiriz (1992)
Phenol	Phenol resins	97	p	200	Demiriz (1992)
Formaldeh.	Plywood production	80	1,450 (p)	426	Mackowiak (1992)
			BIOSCRUBBERS		
Odour	Fish feed product.	95	25,000	581	Hansen & Rindel (1992)
VOCs	Surface coating	>99	26,000	58	Schippert (1989a)
Phenol	Foundry	>94	36,000		Büren (1989)
Ammonia	Foundry	>50	"		"
Methanol		>96	40,000	1428	Wolff (1989)

Bioscrubbers

Much higher volumetric loads can be applied in bioscrubbers. The volumes of the bioreactor part are usually larger than the scrubber volumes, e.g. 28 m^3 and 15 m^3 (Hansen 1992) and 270 m^3 and 180 m^3 (Schippert 1989) respectively. There is a wide variety of bioscrubbers design. The bioreactor part can be situated alongside or underneath the scrubber column, or integrated with the scrubber. An integrated scrubber/bioreactor with gas as the continuous phase is known as a biotrickling filter, less well know in off-gas treatment practice is an integrated bioreactor/scrubber with liquid as the continuous phase as described by Wolff (1989) in which the off-gas is dispersed in form of bubbles. This system is only suitable for elimination of very hydrophilic compounds like methanol, nitrobenzol and acetone.

Biofilters and bioscrubbers also have been used for treatment of odour and ammonia from off-gases from intensive stock breeding (mainly piggeries). According to Schirz (1992) for this purpose 300 biofilters and 50 bioscrubbers have been installed in The Netherlands and FRG from 1976 to 1991. However, a great part does not function properly, due to a lack of maintenance by the users. The volumetric load of these biofilters ranges between 250 and 580 m^3 m^{-3} h^{-1}. Most of the apparates are designed for odour reduction. For elimination of ammonia modifications are necessary, which are presently subject of research efforts.

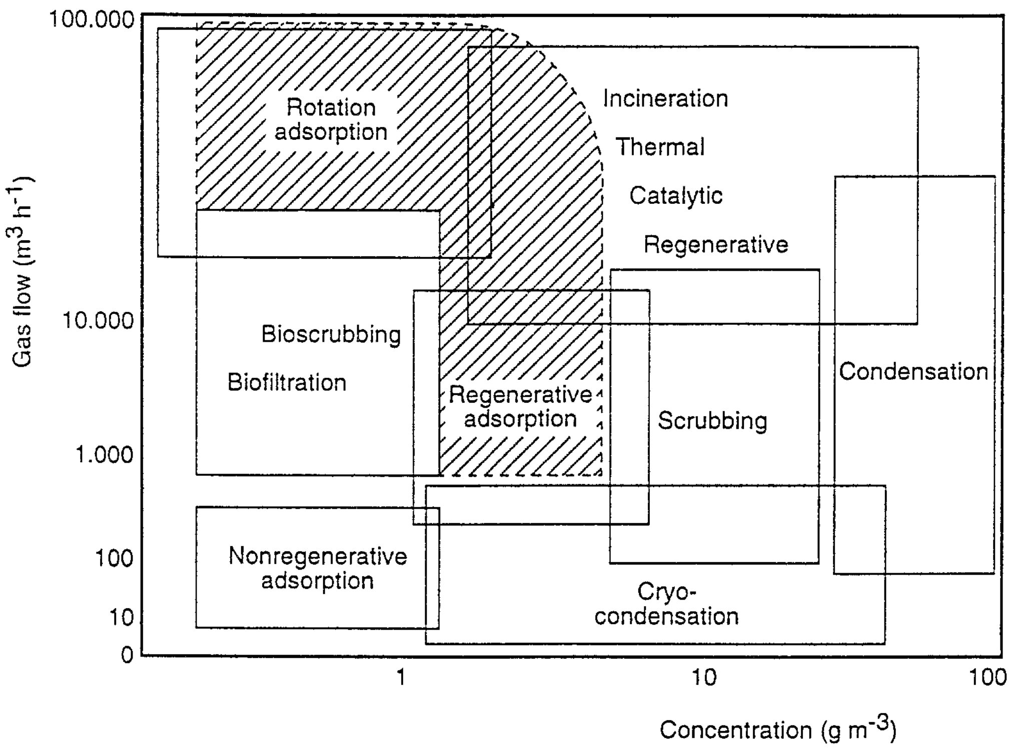

Fig. 4. Application of various techniques for off-gas treatment as function of flow rate and concentration ranges (adapted from Kaiser 1992). The shaded areas indicate recent expansions of the application area of biological techniques.

A biotrickling filter which eliminates more than 90% ammonia has been developed on pilot scale (Demmers 1992). The plant consists of a trickle bed for ammonia absorption and nitrification, a column packed with magnodol for pH buffering and an upflow sludge blanket reactor fed with methanol for denitrification. The stability of the process is still causing problems.

Off-gas from a broiler chicken house, containing 2–30 ppm ammonia, was treated using a biofilter (Pearson et al. 1992). At lower concentrations 50% of the ammonia was removed, but at higher concentrations (30 ppm) the removal efficiency was lower. Additional water was used to sprinkle the biofilter and an effluent containing nitrate, ammonium and BOD was produced.

Comparison to other techniques

Alternative techniques for off-gas treatment are (Joziasse & Wiering 1992):

- Centrifugation using gascyclones for removal of particles and aerosols.
- Adsorption on activated carbon for removal of VOCs, H_2S, SO_2 and CS_2. The activated carbon can be regenerated or discharged and replaced. By rotation adsorption, using disks rotating over a gas phase and a liquid phase, a continuous absorption and desorption can be obtained.
- Scrubbing of flue gases by which volatile acid compounds like SO_2, HCl, HF and NO_x are absorbed in (alkalic) liquids.
- Scrubbing of off-gases by which VOCs, SO_2, NO_x, HCl, HF, NH_3, Cl_2 and H_2S are absorbed in liquid. The liquid can be discharged or regenerated by thermic desorption, low pressures or stripping.
- Thermic incineration by which combustible compounds are oxidized at a temperature of 750–900 °C for VOCs, H_2S, CO, NH_3, COS, CS_2, H_2 and HCN or 1200 °C for toxic and chlorinated compounds (to guarantee a complete oxidation).
- Catalytic incineration in which compounds mentioned above and NO_x are oxidized at 250–600 °C by the use of a catalyst.
- Filtration using e.g. canvas filters for removal of particles.
- Dry chemical flue gas treatment in which solid alkalic adsorbents or catalysts are used.

- Electrofiltration by which solid or liquid particles are captured on electrodes.
- (Cryo-)condensation by extensive cooling at - 140 °C–10 °C.

Advantages of the described physical/chemical techniques compared to biotechniques are a more complete elimination of particles and inorganic compounds like HCl, HF, Cl_2, HCN and NO_x, a good reliability and the possibility of contaminant recovery (by condensation, electrofiltration and adsorption). Disadvantages are the higher costs, the production of waste (wastewater treatment is usually needed) and occasionally low elimination efficiencies (e.g. using condensation). In practice the choice of techniques depends on the nature of the target contaminant, the desired elimination efficiency, the gas flow rate and the concentration in the gas phase (Fig. 4). Combinations of treatment techniques have been frequently reported, e.g. scrubbing with biofiltration as posttreatment.

Economy of operation

For biotechniques the costs reported vary greatly and are hard to compare, e.g. as a result of differences between countries (legislation, energy costs, etc.). Indications for the investment costs for biofilters are given by several authors. According to Kersting (1992) a biofilter costs Hfl 8–9 /(m^3 off-gas/h), while the ventilation equipment costs Hfl 7–31/(m^3/h). Liebe (1989) indicated Hfl 11–16/(m^3/h) and Joziasse & Wiering (1992) estimated investment costs of Hfl 600–8000 per m^3 filterbed. Investment costs for a 30,000 m^3 h^{-1} BiopurIC biotrickling filter were Hfl 28–34 m^{-3} d^{-1} (Schelzhorn & Vinke 1989).

Operational costs for biofiltration range from Hfl 0.45–0.73 per 1000 m^3 gas treated (Kersting 1992), Hfl 0.6–2.2 per 1000 m^3 (Liebe 1989) to Hfl 0.5–5 per 1000 m^3 (Joziasse & Wiering 1992). Oude Luttighuis (1989) reported an amount of Hfl 0.44–1.8 per 1000 m^3 for operational costs including depreciation. According to Joziasse & Wiering (1992) the total operational costs for bioscrubbing are in the range of Hfl 3–6 per 1000 m^3.

In general, physical/chemical techniques for off-gas treatment require higher investment and operational costs. Investment costs [Hfl/(m^3/h)] range from 10–200 (scrubbers), 25–150 (thermic incineration) and 33–95 (catalytic incineration) (Joziasse & Wiering 1992). The operational costs per eliminated amount of VOC are concentration dependent, as illustrated in Fig. 5.

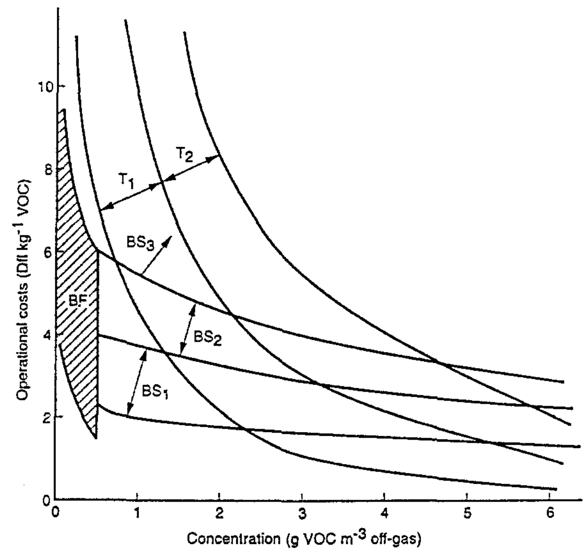

Fig. 5. Operational costs of biofiltration (BF), bioscrubbing of well soluble and biodegradable compounds in continuous operation (BS_1), bioscrubbing of well soluble and biodegradable compounds in discontinuous operation (BS_2), bioscrubbing of poorly soluble and/or poorly biodegradable compounds (BS_3), continuous thermic incineration (T_1) and discontinuous thermal incineration (T_2) at influent gas flow rates of 5,000 and 20,000 m^3 h^{-1} (adapted from Kok 1992).

Concluding remarks

As a result of the growing interest in biotechniques for off-gas treatment, a strong increase of the number of practical applications as well as of the numbers of publications and conferences on the subject can be observed. It is realized that these techniques are an efficient and cost effective method for more than odour reduction only. The application area is still expanding: higher flow rates and higher concentrations can be treated. Although the systems are most suitable for elimination of well water-soluble and biodegradable contaminants, a clear extension to xenobiotic and hydrophobic compounds is going on. At present research and development for such new applications is focussed on elimination of hydrophobic and inorganic compounds, mixtures of contaminants, increase of volumetric capacity, shortening of the adaptation period, reliable and constant operation at fluctuating loads and elucidation of kinetics and microbiology. Although microbiological processes form the basis of the systems, still a lack of understanding is observed in this field. Therefore thorough study of the microbiology in biotechniques for air pollution control is needed. The mentioned R & D efforts may result in an application of biotechniques in areas in which presently regenerative or rotation adsorption and incineration are mostly applied. In fact, biological off-gas treatment can be regarded as a form of catalytic incineration adapted for concentrations below 5–10 g m^{-3}. In the process of extension, transfer of know how from a relatively small number of specialists to potential users and consultancy firms is essential. At present, implementation and demonstration lags behind R & D results and the potential of biotechniques. If such barriers are removed, biotechniques could play a justified and important role in air pollution control in the coming years.

Acknowledgement

J.H. Wolsink (TNO Institute of Environmental and Energy Technology, Department of Air Pollution Control) is gratefully acknowledged for helpful advice.

References

Adamse AD, Deinema MH & Zehnder AJB (1984) Studies on bacterial activities in aerobic and anaerobic waste water purification. Antonie van Leeuwenhoek 50:665–682

Bach H (1923) Schwefel im Abwasser. Gesundheits-Ingenieur 46:370

Braun-Lüllemann A, Majcherczyk A, Tebbe N & Hüttermann A (1992) Bioluftfilter auf der Basis von Weißfäulepilzen. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 91–95). Elsevier, Amsterdam

Bronnenmeier R & Menner M (1992) Reinigung formaldehydhaltiger Abluft in einer Pilotanlage unter Einsatz einer “Start-Kultur”. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 265–272). Elsevier, Amsterdam

Büren E (1989) Bio-catalytische Abgasreinigung in einer Kernmacherei. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 89–107). VDI Verlag, Düsseldorf

Cesário MT, Beeftink HH & Tramper J (1992) Biological treatment of waste gases containing poorly-watersoluble pollutants. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 135–140). Elsevier, Amsterdam

Cho KS, Hirai M & Shoda M (1992) Enhanced removal efficiency of malodorous gases in a pilot-scale peat biofilter inoculated with *Thiobacillus thioparus* DW44. J. Ferment. Bioeng. 73 (1):46–50

Cox HHJ, Doddema HJ & Harder W (1993a) Application of styrene degrading fungi in biofilters. In: Proceedings Conference on Precision Process Technology, Perspectives for Pollution Prevention, Delft, The Netherlands, 27–29 October 1992 (in press)

Cox HHJ, Houtman JHM, Doddema HJ & Harder W (1993b) Growth of the black yeast *Exophiala jeanselmei* on styrene and styrene-related compounds. Appl. Microbiol. Biotechnol. 39:372–376

Cox HHJ, Houtman JHM, Doddema HJ & Harder W (1993c) Enrichment of fungi and degradation of styrene in biofilters. Biotechnol. Letters 15:737–742

De Heyder B, Smet E, Verstraete W & Van Langenhoven H (1992) Biotechnological removal of ethene from waste gases. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 309–313). Elsevier, Amsterdam

Demiriz AM (1992) Neue Einsatzgebiete biologischer Filteranlagen: Gießerei-Bereich und Lösemittelabscheidung. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 293–296). Elsevier, Amsterdam

Demmers TGM (1992) Ammoniakverwijdering uit lucht door middel van biowassers. Proces Technologie Sept. 1992:37–41

Diks RMM & Ottengraf PP (1991) Verification studies of a simplified model for the removal of dichloromethane from waste gases using a biological trickling filter. Bioproc. Eng. 6: 93–99 (part 1), 131–140 (part 2)

Diks RMM (1992) The removal of dichloromethane from waste gases in a biological trickling filter. PhD Thesis, Technical University Eindhoven, The Netherlands

Dolfing J & Tiedje JM (1987) Growth yield increase linked to reductive dechlorination in a defined 3-chlorobenzoate degrading methanogenic coculture. Arch. Microbiol. 149:102–105

Don JA & Feenstra L (1983) European Patent NL 8104987

Don JA (1986) The rapid development of biofiltration for the purification of diversified waste gas streams. In: VDI Berichte 561: Geruchsstoffe (pp 63–73). VDI Verlag, Düsseldorf.

Dragt AJ (1992) Opening address. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 3–9). Elsevier, Amsterdam

Dragt AJ & Ham J van (Eds) (1992) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991. Elsevier, Amsterdam

Eitner D (1989) Vergleich von Biofiltermedien anhand mikrobiologischer und bodenphysikalischer Kenndaten. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 191–213). VDI Verlag, Düsseldorf

Eitner D (1992) Emissionsminderung in Ölmühlen durch Biofilter – Erfahrungsbericht. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 197–205). Elsevier, Amsterdam

Engesser KH (1992) Review paper: Mikrobiologische Aspekte der biologischen Abluftreinigung. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 33–40). Elsevier, Amsterdam

Fischer K (1992) Vergleichende Untersuchungen: Biofilter- oder Biomembranverfahren zur Reinigung lösemittelhaltiger Industrieabluft. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air

Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 97–102). Elsevier, Amsterdam

Folsom BR, Chapman PJ & Pritchard PH (1990) Phenol and trichloroethylene degradation by *Pseudomonas cepacia* G4: Kinetics and interactions between substrates. Appl. Environ. Microbiol. 56 (5):1279–1285

Fritsche K & Lechner U (1992) Einsatz eines chlorphenolverwertenden Bakterienstammes zur Abluftreinigung im Biofilter. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 287–292). Elsevier, Amsterdam

Gils HW van (1964) Bacteriology of activated sludge. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands

Ginkel CG van, Welten HGJ & Bont JAM de (1987) Growth and stability of ethene-utilizing bacteria on compost at very low substrate concentrations. FEMS Microbiology Ecology 45:65–69

Groenestijn JW van, Wolsink JH, Harkes MP, Hesselink PGM, Hecht V, Falk M, Brebbermann D, Bischoff H, Swannell RPJ, Gibson, NB, Passant, NR & Woodfield M (1992) Biofiltration and bioscrubbing of mixtures of volatile organic compounds and trichloroethylene: initial experiments, report 2 EC-STEP project No 900431

Groenestijn JW van, Hesselink PGM & Roos C (1993) Microbiologie bindt de strijd aan met emissies. PolyTechnische Tijdschrift 48(5):36–39

Hansen NG & Rindel K (1992) Recent experience with biological scrubbers for air pollution control in Denmark. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 143–154). Elsevier, Amsterdam

Harder W & Dijkhuizen L (1982) Strategy of mixed substrate utilization in microorganisms. Phil. Trans. R. Soc. Lond. B 297:459–480

Hartmans S, Leenen EJTM & Voskuilen GTH (1992) Membrane bioreactor with porous hydrophobic membranes for waste-gas treatment. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 103–106). Elsevier, Amsterdam

Henson JM, Yates MV & Cochran JW (1989) Metabolism of chlorinated methanes, ethanes, and ethylenes by a mixed bacterial culture growing on methane. J. Industr. Microbiol. 4:29–35

Hofmann W (1989) Biofilter nach Kakaoröstereien. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 233–242). VDI Verlag, Düsseldorf

Holliger C (1992) Reductive Dehalogenation by Anaerobic Bacteria. PhD thesis, Wageningen Agricultural University, The Netherlands

Huber J (1992) Planung, Durchführung und erste Erfahrungen zum Biofilter Tierkörperbeseitigungsanlage Plattling. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 161–166). Elsevier, Amsterdam

Hübner R & Saake M (1989) Einsatz von Biofiltern zur Behandlung lösemittelhaltiger Abluft. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 277–284). VDI Verlag, Düsseldorf

Janssen DB, Oldenhuis R & Wijngaard AJ van den (1989) Degradation of xenobiotic compounds by microorganisms. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 25–39). VDI Verlag, Düsseldorf

Joziasse J & Wiering ACF (1992) Monografieën informatiesysteem technieken. Compartiment Lucht. TNO/RIVM Report Nr. 736101007

Kaiser W (1992) Beschikbare nageschakelde technieken voor de bestrijding van VOS-emissies via puntbronnen. PetroChem 4:18–19

Kersting U (1992) Behandlung großvolumiger Abluftströme durch Biofilter, vorgestellt an Beispielen der Tabakindustrie. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 155–160). Elsevier, Amsterdam

Kirchner K, Hauk, G & Rehm HJ (1987) Exhaust gas purification using immobilised monocultures (biocatalysts). Appl. Microbiol. Biotechnol. 26:579–587

Kirchner K (1990) Biological purification of exhaust air. Chimica*oggi* March 1990: 51–55

Kluy MJ & Reddy CA (Eds) (1984) Current Perspectives in Microbial Ecology. Am. Soc. for Microbiol., Washington DC, USA

Kok HJG (1992) Bioscrubbing of air contaminated with high concentrations of hydrocarbons. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 77–82). Elsevier, Amsterdam

Konings JHG & Ottengraf SSP (1988) The emission of microorganisms from biofilters. In: Proceedings 2nd Netherlands Biotechnology Congres, Amsterdam, 20–21 October 1988.

Leson G & Winer AM (1991) Biofiltration: an innovative air pollution control technology for VOC emissions. J. Air Waste Manage. Assoc. 41 (8):1045–1054

Liebe HG (1989) Einsatz von Biofiltern zur Minderung der Emissionen von Anlagen zum Verarbeiten von Fleish und Fisch für die menschliche Ernährung. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 215–231). VDI Verlag, Düsseldorf

Mackowiak J (1992) Abscheidung von Formaldehyd aus der Abluft im Biofilter. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 273–278). Elsevier, Amsterdam

Maier G (1989) Biofiltration von Gießereiabgassen. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 285–292). VDI Verlag, Düsseldorf

Majcherczyk A, Braun-Lülleman A & Hüttermann A (1990) Biofiltration of polluted air by a complex filter based on white-rot fungi growing on lignocellulosic substrates. In: Coughlan MP & Amaral Collaço MT (Eds) Advances in Biological Treatment of Lignocellulosic Materials (pp 323–329). Commission of the European Communities, Elsevier Applied Sciences, London, New York

Meer JR van der, Zehnder AJB & Vos WM de (1991) Identification of a novel composite transposable element, Tn5280, carrying chlorobenzene dioxygenase genes of *Pseudomonas* sp. strain P51. J. Bacteriol. 173:7077–7083

Meer JR van der (1992) Molecular Mechanisms of Adaptation of Soil Bacteria to Chlorinated Benzenes. PhD thesis, Agricultural University Wageningen, The Netherlands

Meulen B ter (1991) Membrane technology could play a major role in reducing emissions. Appl. Research 37:3

Mildenberger HJ (1992) Biofiltersysteme zur Geruchsbeseitigung und zur Reduzierung von Organika-Emissionen auf Kläranlagen und in der chemischen Industrie. In: Dragt AJ & Ham J van (Eds)

Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 187–196). Elsevier, Amsterdam

Nolte FJ (1992) Ermittlung der Eliminationsleistung eines Biofilters bei der Behandlung von Ethylacetatablüften – halbtechnische Pilotanlage. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 297–302). Elsevier, Amsterdam

Ottengraf SPP & Oever AHC van den (1983) Kinetics of organic compound removal from waste gases with a biological filter. Biotechnol. Bioeng. 25:3089–3102

Ottengraf SPP (1986) Exhaust gas purification. In: Rehm HJ & Reed G (Eds) Biotechnolgy Vol. 8 (pp 425–452) VCH Verlagsgesellschaft, Weinheim

Ottengraf SPP, Meesters JJP, Oever AHC van den & Rozema HR (1986) Biological elimination of volatile xenobiotic compounds in biofilters. Bioproc. Eng. 1:61–69

Ottengraf SPP (1987) Biological systems for waste gas elimination. Tibtech 5:132–136

Ottengraf SPP & Diks RMM (1992) Process technology of biotechniques. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 17–31). Elsevier, Amsterdam

Oude Luttighuis H (1989) Möglichkeiten für Biofiltration in der pharmaceutischen Industrie. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 341–348). VDI Verlag, Düsseldorf

Pearson CC, Phillips VR, Green G & Scotford IM (1992) A minimum-cost biofilter for reducing aerial emissions from a broiler chicken house. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 245–254). Elsevier, Amsterdam

Poppe W & Schippert E (1992) Das KCH-Biosolv-Verfahren in Kombination mit einem Biowäscher herkömmlicher Art – eine Verfahrensentwicklung zur Abluftreinigung für wasserlösliche und schwer wasserlösliche Schadstoffe. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 71–76). Elsevier, Amsterdam

Rieneck MG (1992) Mikrobiologische Methoden zur Charakterisierung von Biofiltermaterialien. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 85–95). Elsevier, Amsterdam

Riet K van 't & Tramper J (1991) Basic Bioreactor Design. ISBN 0–8247–8446–4, Marcel dekker Inc., New York, Basel, Hong Kong

Roos C & Fischer K (1989) Konstruktionsmöglichkeiten für Biofilter. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 179–189). VDI Verlag, Düsseldorf

Sabo F (1989) Praktische Erfahrungen mit Biofiltern zur Reinigung geruchsintensiver Deponiegase. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 293–312). VDI Verlag, Düsseldorf

Schelchshorn J & Vinke A (1989) Erfahrungsbericht über die mikrobielle Entschwefelung von Biogasen auf Kläranlagen nach dem BiopurIC-Verfahren. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 129–138). VDI Verlag, Düsseldorf

Schippert E (1989a) Biowäscher nach einer Dosenlackieranlage. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 77–89). VDI Verlag, Düsseldorf

Schippert E (1989b) Das Biosolv-Verfahren von Keramchemie zur Absorption von schwer wasserlöslichen Lösemitteln. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 161–177). VDI Verlag, Düsseldorf

Schirz S (1992) Stand der Technik bei der biologischen Abluftreinigung in der Intensivtierhaltung. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 237–244). Elsevier, Amsterdam

Slater JH & Godwin D (1980) Microbial adaptation and selection. In: Ellwood DC, Hedges JN, Latham MJ, Lynch JM & Slater JH (Eds) Contemporary Microbial Ecology. Academic Press, London.

Swannell RPJ, Richardson SJ, Passant NR, Woodfield M, Lugt JP van der, Wolsink JH, Hesselink PGM, Hecht V, Brebbermann D & Bischoff L (1991) Biodegradability and emissions of volatile organic compounds from the food, drink and metal degreasing industries, report 1 EC-STEP project No 900431

Tramper J, Wolters I & Verlaan P (1987) The liquid-impelled loop reactor: a new type of density-difference-mixed bioreactor. In: Laane C, Tramper J & Lilly MD (Eds) Biocatalysis in Organic Media (pp 311–316). Elsevier, Amsterdam

VDI Berichte 735 (1989) Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen. VDI Verlag, Düsseldorf

Weber FJ & Hartmans S (1992) Biological waste gas treatment with integrated adsorption for the treatment of fluctuating concentrations. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 125–130). Elsevier, Amsterdam

Windsperger A (1992) Optimierung von biologischen Abluftreinigungsanlagen an praktischen Beispielen. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 107–117). Elsevier, Amsterdam

Wolff F (1989) Biologische Abluftreinigung mit einem neuen Biowäscherkonzept. In: VDI Berichte 735: Biologische Abgasreinigung, Praktische Erfahrungen und Neue Entwicklungen (pp 99–107). VDI Verlag, Düsseldorf

Wolff F (1992) Biologische Abluftreinigung mit einem intermittierend befeuchteten Tropfkörper. In: Dragt AJ & Ham J van (Eds) Biotechniques for Air Pollution Abatement and Odour Control Policies, Proceedings of an International Symposium, Maastricht, The Netherlands, 27–29 October 1991 (pp 49–62). Elsevier, Amsterdam