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Research review paper

Biomass accumulation and control strategies in gas biofiltration

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ABSTRACT

Uneven distribution and excess accumulation of biomass within gas phase biofilters often result in operational problems such as clogging, channeling, and excessive head loss within biofilter beds, and consequently, the deterioration of performance. In this paper, the characteristics, mechanisms, and patterns of biomass accumulation in gas biofiltration were reviewed, and models for biomass accumulation were also summarized. Strategies for excess biomass control in gas biofiltration, categorized into either physical, chemical, or biological methods were also discussed, with improvements in design and operation of biofilters. Combinations of these approaches are usually necessary in order to maintain a reasonably even distribution and to minimize the accumulation of biomass in gas biofilters.

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1. Introduction

In the last few decades, emission control of volatile organic compounds (VOCs) and other odorous pollutants has become a crucial issue due to their adverse effects to humans, animals, and the environment. VOCs can affect the health of humans and animals adversely on both short and long terms, participate in the formation of photochemical smog, ozone and respirable suspended particulates in

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the atmosphere, and can result in sharp declines in crop yields, and the destruction of forests and ecosystems. Odor emission is a common environmental problem that is not only a public health concern, but also a threat to personal comfort (Leuch et al., 2003).

Legislation on emission control of VOCs and other odorous pollutants has proliferated worldwide (van Groenestijn and Kraakman, 2005; Guieysse et al., 2008). Since the enactment of the 1990 Amendments to the Clean Air Act (CAA), technologies including adsorption, absorption, condensation, incineration, flaring, and biological control methods have been developed for the removal of VOCs and odors from waste gases. Biological processes for air pollution control have become established technology for the control of emissions of VOCs, odors, or other hazardous air pollutants (Deshusses, 1997).

In a gas biofiltration process, pollutants from waste gases are degraded into environmentally benign end-products when gases pass through biologically active media on which biofilms attached (Zhu et al., 1996). At present, gas biofiltration has been considered to be a cost-effective and reliable technology for control of low-concentration waste gases contaminated by VOCs and other odors (Deviny et al., 1999). It has also been environmentally friendly technology due to environmentally benign end-products of water and carbon dioxide (Alonso et al., 1998).

Existing biofilters for waste gas treatment can be classified as traditional biofilters, biotrickling filters (BTFs), bioscrubbers, and new types of biofilters (Deshusses, 1997; Cox and Deshusses, 1998; Yang et al., 2003a).

BTFs offer lower operating cost, convenient operation, small footprint, and low resistance (Deshusses and Webster, 2000; Iranpour et al., 2005). Since 1923 when biofiltration was first used for controlling the emission of hydrogen sulfide from a wastewater treatment plant, gas biofiltration has been applied to treat various waste gases including various VOCs (Leson and Smith, 1997; Wiczorek, 2005; Grove et al., 2009), hydrogen sulfide (Sercu et al., 2005), ammonia (Pagans et al., 2007), sulfur dioxide (Philip and Deshusses, 2003), and nitrogen oxides (du Plessis et al., 1998). Up to this century, over 7500 biological waste gas treatment systems and related systems have been installed all over Europe, half of which have been installed at sewage treatment plants and composting sites (van Groenestijn and Kraakman, 2005). Furthermore, the application of biofiltration technology throughout the world will continue to grow throughout the twenty-first century (Deviny et al., 1999).

Although biofiltration has many advantages, there are also some problems for existing biofiltration technologies. Included among these are the uneven distribution and excess accumulation of biomass within biofilter beds. Biomass is a critical factor in gas biofiltration, and uneven distribution and excess accumulation within gas biofilters often result in operational problems such as clogging, excessive head loss, and channel formation of gas streams within biofilter beds, which leads to deterioration in performance (Yang et al., 2003a).

Many investigations on biomass accumulation have been carried out for a better distribution of biomass and lower rates of biomass accumulation within biofilter beds so that a longer duration of stable performance of biofilters could be reached (Alonso et al., 1998; Okkerse et al., 1999; Yang et al., 2003a). Packing materials, nutrients, and the flow fields of waste gases for biofilters has been optimized for optimal growth conditions for the microbes in biofilms and consequent better performances in gas biofiltration (Malhautier et al., 2005). Methods for control of excess biomass by physical, chemical, and biological means have been studied (Smith et al., 1996; Cox and Deshusses, 1999a,b; Moe and Irvine, 2000; Kennes and Veiga, 2002; Yang et al., 2003b). Innovative biofilter designs and operational strategies have also been studied (Vinage and von Rohr, 2003a,b; Yang et al., 2004; Carvalho et al., 2009; Moe et al., 2007).

Several reviews are also available on gas biofiltration technology (Ottengraf, 1987; Edwards and Nirmalakhandan, 1996; Deshusses, 1997; Cox and Deshusses, 1998; Grommen and Verstraete, 2002; Kennes and

Veiga, 2002; Gavrilesco and Chisti, 2005; Delhomenie and Heitz, 2005; Doble, 2006). Kennes and Veiga (2002) review strategies for the control of excessive biomass accumulation, and group these strategies into four categories as the use of mechanical forces, the use of specific chemicals, the reduction of microbial growth, and the use of predation.

Recently, more investigations on biomass accumulation mechanisms have been carried out, and many progresses concerning innovations on biofilter design and operational modes for excess biomass control have also been made. Therefore, a comprehensive review on the characteristics, mechanisms, and kinetics of biomass accumulation as well as control strategies will lead to a better understanding of biofiltration and a better design and operation of biofilters.

2. Biomass accumulation

2.1. Development and structure of biofilms

Biofilms are a sort of biological communities in which microorganisms adhere together and embed in a polymer matrix (Craig, 2002). Adherence of microorganisms to surfaces of a support medium is very important for the initiation of biofilm development (Hall, 1987; Costerton et al., 1995; Chávez et al., 2006). Reynolds and Fink (2001) confirm that bakers' yeast *Saccharomyces cerevisiae*, when growing on low-glucose medium, can adhere avidly to many plastic surfaces and lead to the formation of biofilms. Microorganisms are attached on the support media in a biofilter for treatment of wastewater or waste gas streams (Cohen, 2001). Different from naturally formed biofilms, artificial biofilms in bioreactors are constructed intentionally in settled conditions. During the development of biofilms, microorganisms can be immobilized to a supporting medium through the attachment of microorganisms themselves or engineered measures (Cohen, 2001). Liu and Tay (2002) classify the development of biofilms into the following steps, including contact and aggregation between microorganisms or attachment of a microorganism on a supporting medium due to physical movement and initial attractive forces, development of aggregated or attached microorganisms due to microbial forces, and formation of polymer matrix structure of biofilms due to hydrodynamic shear forces. Annachatre and Bhamidimarri (1992) consider biofilm formation during the startup period of fixed-film reactors can be significantly affected by environmental, cellular and surface factors. Bayles (2007) thinks genomic DNA released from decomposition of dead microorganisms plays an important role in development and stability of biofilms. Extracellular polymeric substances (EPSs) produced by mature microbes as a component of biofilms also contributes significantly to the accumulation of biofilms. Costerton et al. (1995) consider bacterial cells in biofilms secrete EPSs that help combine the cells together.

Structure and functions of biofilms are believed to interact significantly. Therefore, investigations on biofilm structure have been performed extensively at various scales. Within mature biofilms, there are channels and microchannels where fluid can fill, permeate or flow through, and microorganisms in pillars can exist (Costerton et al., 1995). Cohen (2001) believes that glycocalyx play a key role in attachment of biofilms. The constructed biofilms in biofilters have similar characteristics and architecture to the biofilms formed naturally, such as dense, highly hydrated clusters of bacterial cells and elaborate structures. Some cell-free channels existed and extended from the biofilm–liquid interface to the substratum, and possibly enhanced pollutant and oxygen mass transfer. A well established biofilter is a complex and structured ecosystem. Malhautier et al. (2005) think the interacted microorganisms and microzoa constitute a complex, structured and flexible ecosystem in a biofilter with their surroundings. The dynamic and self-regulated ecosystem has its own circulation of materials and energy, and relatively stable microbial communities. Microbial communities are sensitive to variations in environmental conditions in gas phase biofilters, therefore, understanding of the microbial ecology of

biofilms in gas phase biofilters helps optimize design and operations of such biological treatment systems (van Groenestijn and Hasselink, 1993). Biofilms within which there are a significant heterogeneity are different from suspended bacteria in both morphology and physiology (Cohen, 2001; Davies et al., 1998), and Davies et al. (1998) report that there exists cell-to-cell signaling in the development of bacterial biofilms.

Some advanced analysis methods incorporated with conventional analyses are used for investigations on biofilms. Conventional methods are performed to measure important cellular components including EPSs, proteins, hydrolase, dehydrogenase and total polysaccharides (Bihan and Lessard, 2000). Villaverde et al. (1997) use a microsensor and a microscopic examination of the cryosections of biofilms to determine the toluene-oxidizing cells. Grove et al. (2004, 2007) use BIOLOG ECO-plates to investigate the spatial and temporal variations of the bacterial community in a compost biofilter for ethanol removal, and show that BIOLOG ECO-plates are appropriate for the study on changes of community in biofilters. Modern analytical methods which involve confocal laser scanning microscopy (CLSM), microautoradiography (MAR), polymerase chain reactions (PCR), and quantitative reverse transcriptase real-time PCR (qRT-PCR) are also applied to investigate the structure of biofilms (Stewart and Franklin, 2008). Microprobe sensors and modern molecular biotechnologies (Zhu et al., 2001, 2004) including PCR, denaturing gradient gel electrophoresis (DGGE), and fluorescent in situ hybridization (FISH) (Yang, 2004) have been successfully applied to the investigation of the structural and microbial composition of biofilms and the distribution of contaminants and oxygen on micrometer or molecular level in gas phase biofilters. Delatolla et al. (2009) recommend an analytical protocol which uses tools including environmental scanning electron microscopy, confocal laser scanning microscopy and FISH to non-destructively measure the biological community structure of nitrifying biofilms for wastewater treatment facilities. Okkerse et al. (2000) present a laser triangulation sensor system which can quickly measure surface roughness and thickness of biofilms in a BTF without destructive procedures for sample preparation. The experimental tools for biofilm analysis are summarized in Table 1.

2.2. Consequences of excess biomass accumulation

With the gradual accumulation of attached biomass over long periods of operation, some operation problems eventually emerge in

biofilters. Uneven biomass accumulation and consequent biological clogging are usually considered to be among the major problems in the media of gas phase biofilters (Moe and Qi, 2004; Zhu et al., 2004).

Stewart and Franklin (2008) think there exists a maximal biofilm thickness along the medium depth in biofilm systems due to the existence of concentration profiles for substrates and metabolic products. When concentrations of the contaminants decline as the air passes through the biofilters, the characteristics of microbial flora changes accordingly. Song and Kinney (2000) report higher biomass concentrations and thicker biofilm layers near the inlet of a biofilter. Alonso et al. (1998, 2000) consider uneven biomass distribution leads to some operational problems including clogging, short-circuiting, and increased pressure drop, and deteriorated removal efficiency, especially at high organic loading rates and for a long duration of operation of biofilters. Biomass washed out from different media layers over a period of operation is observed and measured, and more biomass is observed to accumulate in the medium close to the gas inlet in RDBs (Yang et al., 2003a). Moreover, inactive biomass presented in biofilms usually also distributes unevenly. More than 50% of cells in biofilms to which volatile substrates are fed can be inactive. Song and Kinney (2000) report that the concentration of inactive biomass in biofilms gradually increases while the viable biomass concentration does not change during a three-month operation in a celite-packed biofilter. In contrast, Diks et al. (1994) report a steady increase in the endogenous respiration rate for a BTF in which the process eventually become the major carbon dioxide generating process. The inert biomass can include the residues of dead cells, captured suspended solids, and inorganic precipitates. In a cellular automaton model, biomass decay is assumed to be proportional to active biomass (X_{act}), and a fraction of X_{act} is converted into inactive biomass (X_{inact}) such as cell debris and extracellular polymeric substances (Song and Kinney, 2002). Biomass decay is a complicated microbial process that can include endogenous respiration, cell death, and extracellular polymer secretion in the biofilm phase. However, the regulated death of bacterial cells is important for biofilm development (Bayles, 2007).

Excess biomass formation in a biofilter induces progressive clogging of the medium bed and a consequent buildup in pressure drop and flow channeling within the medium bed (Iliuta and Larachi, 2004). Cox and Deshusses (1998) report biomass accumulation rates ranging from 3.1 to 9.8 kg of biomass per cubic meter of reactor per day when VOC loadings range from 20 to 40 g of toluene per cubic meter of reactor per day in a BTF, and significant drop of removal

Table 1
Experimental tools for biofilm analysis.

Experimental tools	Applications	References
Biochemical tests and weight	Measure the content of hydrolase, dehydrogenase (DHA) and total polysaccharides (TP); weigh the amount of biomass	Bihan and Lessard (2000), Yang et al. (2003a) and Yang (2004)
Confocal laser scanning microscopy (CLSM)	Determine cell counts in the biofilm and characterize the undisturbed substratum/biofilm interface	Delatolla et al. (2009) and Stewart and Franklin (2008)
Microautoradiography (MAR)	Characterize the activities of diverse microorganisms in natural biofilm assemblages at the single-cell level with fish	Stewart and Franklin (2008)
Polymerase chain reaction (PCR)	Rapidly amplify the specific genes (DNA) fragments	Yang (2004)
Quantitative reverse transcriptase real-time PCR (qRT-PCR)	Quantitative monitoring the content of certain RNA	Stewart and Franklin (2008)
Denaturing gradient gel electrophoresis (DGGE)	Monitor the community compositions of the VOC degrading cultures; analyze microbial community structure; identify microbial species	Yang (2004) and Zhu et al. (2004)
Fluorescent in situ hybridization (FISH)	Explore the function of biofilms; localize species diversity in natural biofilms	Yang (2004), Delatolla et al. (2009) and Stewart and Franklin (2008)
Environmental scanning electron microscopy (ESEM)	Evaluate the percent coverage of the substratum with biofilm and the biofilm thickness;	Delatolla et al. (2009)
Microprobe sensor	Examine biofilm structure and oxygen concentration distributions along the depth of the biofilms	Zhu et al. (2001, 2004)
Laser triangulation sensor (LTC)	Measure surface roughness and thickness of biological films	Okkerse et al. (2000)
Microsensor	Determine the respiration rate and the toluene-oxidizing cells	Villaverde et al. (1997)
BIOLOG ECO-plates	Investigate the spatial and temporal variations of the bacterial community	Grove et al. (2004, 2007)
Analytical protocol with ESEM, CLSM and FISH	Non-destructively measure the biological community structure of nitrifying biofilms	Delatolla et al. (2009)

efficiency of the biofilter is observed after the biofilter is operated for 3–5 months. Excess biomass accumulation and uneven biomass distribution usually occur simultaneously within porous medium beds after a long period of operation, which leads to operating problems such as biological clogging, channeling, great pressure drop, short-circuiting, deteriorating biofilter performances (Weber and Hartmans, 1996; Delhomenie et al., 2003).

2.3. Mechanisms and patterns of biomass accumulation

Biomass whose major components are bacteria and fungi is a key factor in a biofilter system, because VOCs and odorous compounds are biodegraded by biomass. Devinny et al. (1999) think mass of biomass within a biofilter can reflect its performance. During biofiltration process, biomass accumulate and decay. Therefore, biomass distribution can indicate where VOCs and odorous pollutants are degraded within a biofilter, and consequently imply the removal mechanisms. Excess biomass in biofilters usually leads to drop of removal efficiency for pollutants (Yang et al., 2003a).

Biomass accumulation in gas biofiltration involves the immobilization of microbes, formation of constructed biofilms, accumulation of biomass because of the growth and decay of biofilms, and holdup of the metabolites and solutions. Growth and accumulation of biofilms in packing materials are mainly responsible for the increase of biomass, while degradation and decay of biofilms along with external factors are the primary culprits for biomass loss.

VOCs in waste gas streams are usually the sole or dominant carbon source for biofilms in biofilters, so biofilm growth rate is controlled by the feeding rate of VOCs to the microbes. Therefore, VOC concentration in incoming waste gas streams or VOC concentration profile along a medium bed determines biofilm growth rate in gas phase biofilters. Consequently, the specific growth rate of biofilms near the gas inlet is usually higher than that near the gas outlet (Yang et al., 2003a; Song and Kinney, 1999). Similar results are reported in a biofilter for water treatment (Campos et al., 2002). Song and Kinney (2000) investigate on the temporal and spatial changes in biomass accumulation and activity using two bioreactors in which one is operated in a unidirectional (UD) mode and the other in a directionally switching (DS) mode. Excess biomass accumulate primarily in the inlet section, and the biofilm inactivation process starts earlier and proceed more rapidly toward the outlet section in the UD bioreactor. More even distribution of biomass and higher activity of the total microbial population are obtained in the DS bioreactor than that in the UD bioreactor.

In a gas phase biofilter, the rate of biomass accumulation is equal to the rate of biofilm growth minus the rate of biofilm decay which is resulted from detachment or hydraulic scouring. Therefore, equations for modeling the variation of the biofilm thickness with time can be established by the item of bacterial growth and the item of bacterial decay (Alonso et al., 1997, 1998).

$$\frac{\partial L_f}{\partial t} = \left(r_d D_w \frac{\partial C_f}{\partial x} \Big|_{x=L} \right) \frac{Y}{X_f} - L_f b \quad (1)$$

$$b = b_s + b_d \quad (2)$$

where L_f is the biofilm thickness, r_d the ratio between VOC diffusivities in biofilm and water, D_w the contaminant diffusivity in water, C_f the VOC concentration in the biofilm, Y the yield coefficient, X_f the film bacterial density, b the specific shear/decay coefficient, b_d the specific decay coefficient, and b_s the specific shear rate.

Factors including the thickness and age of biofilms, the availabilities of oxygen and carbon source as well as nutrients, the concentrations of metabolism products, and the composition and activity of biofilms considerably affect biofilm decay rate. The death and lysis of microbial cells and the aging sloughs of biofilms usually help lead to biofilm detachment. Biofilms can also be sheared by the

flowing liquid along the interspaces and channels around or within biofilms. In a biofilm reactor, hydrodynamic shear force which is considered to play an important role in biofilm development may result from fluid flowing or attrition between particles. Shear force by liquid flow can affect considerably biofilms in many aspects including structure, mass transfer, exopolysaccharides production, metabolic and genetic properties, however, little information on genetic changes of microorganisms within biofilms due to shear-force scouring is currently available (Liu and Tay, 2002).

Biodegradation within biofilms is mediated by mixed cultures of bacteria and fungi thriving in a complex ecosystem where there are also secondary pollutant degraders and predators such as protozoa and other higher organisms. The overall biomass accumulation rate not only depends on the growth rate of primary degraders, but also on the rate of secondary processes probably including endogenous respiration, cryptic growth and predation of bacteria by higher organisms (Cox and Deshusses, 1998). No net accumulation of biomass during the operation of a biofilter has also been reported by Diks et al. (1994), because the overall rate of CO_2 production has slowly increased and finally counter-balanced the conversion rate of dichloromethane (DCM) on a molar basis.

Many factors have contributed to biomass accumulation in biofilters. Generally, the intentionally engineered biofilms attach on the media on which microorganisms are attached through adhesion commonly regulated by reversible adhesion kinetics (Rittmann et al., 2002). Although any materials other than organic contaminants, water or nutrient solutions are not needed adding to biofilters, it is reasonable for biofilters to be operated under some favorable conditions such as micronutrient additions and proper temperature in order to attain satisfactory performance and to favor rapid biofilm development and biomass accumulation. Many other factors affect biofilter performance, such as mass transport, spatial and temporal distributions of carbon source and nutrients as well as oxygen in biofilms, biochemical reaction kinetics of the contaminant(s), rules of microorganism metabolism and reproduction, microbial competition and inhibition, biofilm attachment and detachment, microbial ecology of biofilms, biomass accumulation dynamics, and biofilter configuration (Cox and Deshusses, 2002).

Growth and accumulation of biomass within biofilters can permanently reshape the pore structure of biofilter bed (Iliuta et al., 2005), and change the biofilm-specific surface area (Alonso et al., 1997, 1998; Yang et al., 2009a,b), which may in turn affect the growth of biofilms, accumulation of biomass, and performance of a biofilter.

According to the biomass concentration–depth profile among various medium layers in multi-layer RDBs, Yang et al (2003a) and Yang (2004) propose four types of biomass accumulation patterns which are surface, in-depth, shallow, and reverse patterns. The surface and in-depth patterns are two extreme scenarios. The surface pattern occurs when most biomass are accumulated on the outermost surface of the medium layer, while the in-depth pattern is used to describe the state when biomass is distributed evenly throughout the medium depth. Cases between these two extreme scenarios are classified as the shallow pattern. In the reverse pattern, biomass concentrations in some of the inner medium layers are larger than that in the outermost medium layer. Although these biomass accumulation patterns are observed from and proposed for RDBs, it should be noted that profiles of VOC or biomass concentration along medium bed in BTFs and other biofilters have also reported or discussed by Song and Kinney (1999, 2000), Zhu (2000), Yang and Allen (2005), etc. Therefore, there also exist various biomass accumulation patterns for other biofilters although more investigations are needed.

Mathematical models have been developed to estimate the biomass accumulation rates in the outermost, middle, and innermost layers of a multi-layer RDB, and the simulation results further support the speculation that there exist various biomass accumulation patterns (Yang et al., 2006). In the models, the biofilm growth

equations are similar to Eqs. (1) and (2), while biomass accumulation rates are calculated using the following equation

$$\text{VSS accumulation rate} = \frac{X_f \times (\varepsilon_0 - \varepsilon_f) \times V'}{t} \quad (3)$$

where ε_0 is the clean bed porosity, ε_f the porosity in the bed with biofilm, and V' the medium volume of each layer of the multi-layer RDB.

In some degree, biomass distribution in the medium can indicate where VOCs are biodegraded, consequently, biomass accumulation pattern may represent mass transport phenomena and removal mechanisms in a biofilter. Therefore, design and operation of any biofilters should take account of biomass accumulation pattern (Yang et al., 2003a).

Yang et al. (2003a) and Yang (2004) report that factors including organic loading rates, gas empty bed contact time (EBCT) values, properties of the target VOCs including water solubility and the Henry's law constant, and biofilter configuration affect which particular biomass accumulation pattern will dominate in biofilters. More investigations in this field are required to predict which biomass accumulation pattern will dominate in a biofilter system, and to control, to some degree, which biomass accumulation pattern will prevail through the adjustment of some design and operating parameters mentioned above (Yang et al., 2003a).

2.4. Modeling of biomass accumulation

Due to the important role of biomass play in biofiltration, it is important to simulate and predict biomass accumulation. Process modeling helps to understand the relationship between parameters and pollutant removal, to predict biofilter performances, to optimize biological processes, and to illuminate the characteristics and mechanisms of biomass accumulation in gas biofiltration. Therefore, modeling of biomass accumulation within porous media has been a research focus for biofiltration.

Biofilm models developed by Stewart and Kim (2004) can well simulate the development, removal, and propagation of biomass-plug and channel breakthrough within medium bed on the basis of the Bingham yield stress of biofilms in biofilm systems. Picioareanu et al. (2007) describe and evaluate a computational model for microbial fuel cells based on redox mediators with several populations of suspended and attached biofilm microorganisms and multiplied dissolved chemical species.

Dynamic mathematical models have been developed to describe physical and biological processes occurring in BTFs, and modeling results show that excess accumulation of biomass affects adversely contaminant removal efficiency (Alonso et al., 1997; 1998). Performances of BTFs for volatile acidifying pollutants removal have been modeled dynamically by accounting of biomass accumulation on the time scale, and the clogging rate of a filter bed and the time it takes the BTF to adapt to changes of the inlet concentration could be predicted (Okkerse et al., 1999). Mathematical models also show that biomass accumulate rates for various sponge medium layers in a RDB with four medium layers are different (Chen et al., 2007), which is consistent with the experimental observations of the four types of patterns for biomass accumulation (Yang, 2004). Dynamic and spatial variations of biofilm thickness within a BTF have also been simulated using dynamic mathematical models (Yang et al., 2009b). A pore network model is developed which can predicate the removal efficiency and pressure drop due to biomass accumulation at the pore level (Schwarz et al., 2001; Nukunya et al., 2005). Song and Kinney (2002) develop a numerical model which accounts for inactive biomass in biofilms to predict long-term performance of gas bioreactors, and a cellular automaton approach is adopted to simulate the changes of biomass growth and biofilm thickness. The modeling results show deteriorat-

ing removal efficiency of a biofilter after a long duration of operation is due to a decrease in both the active fraction and the specific surface area of biofilms. Morales et al. (2003) report a one-dimensional dynamic model to describe drying and its effect on the performance of biofilter packed with peat, and simulation results show that water evaporation from the packing materials due to exothermic metabolic reactions and moistures in the incoming air streams deteriorates biofilter performance.

The effect of biomass accumulation on operating parameters has also been investigated using modeling approach. Morgan-Sagastume et al. (2001) develop a model to predict biomass-affected porosity and pressure drop within porous medium bed as a function of biomass concentration on the basis of the Ergun equation. Porosity variations with time and sponge medium layers in a multi-layer RDB for toluene removal at different organic loadings and gas EBCTs are also estimated using a diffusion-reaction model in which biofilm growth and decay are taken into account at medium-pore scale (Yang et al., 2009a). Okkerse et al. (1999) calculate that maximum organic loading rate should not exceed 0.5–1.6 mol of carbon per hour per cubic meter of void packing volume for a BTF when applied to purify dichloromethane contaminated air streams.

Although many investigations have been conducted on biomass accumulation, Devinny and Ramesh (2005) think biofilter modeling remains primarily a research tool up to now. This is mainly due to the following reasons. First, there exist inexactness in the development of models and difficulty in the estimation of model parameters. Second, biofilms are complex systems due to the heterogeneity of biofilm phase, the diversity of microorganisms, and the uncertainty of biomass compositions. At last, properties of target pollutants can be different dramatically. For example, mathematical models based on adsorption–biodegradation processes are widely accepted for process modeling in gas biofiltration, while absorption–biodegradation models are likely to be more suitable for the removal of hydrophobic pollutants. Grove et al. (2009) think more detailed information on pathway of biodegradation of octane is required to dynamically model octane removal in a biofilter. Therefore, more investigations are needed before biofilter modeling can be used in the design and operation of biofilters.

3. Biomass control strategies for gas-phase biofilters

Excessive biomass accumulation which can be predicated using mathematical models will lead to deteriorating performance of biofilters. Therefore, it is necessary to take strategies either to remove excess biomass from biofilter systems or to prevent uneven distribution of biomass within media, so that biofilters can maintain stable removal efficiency over a long duration of operation. Biomass control methods are grouped in the following five groups: physical methods, chemical methods, biological methods, improved biofilter designs, and improved operation modes.

3.1. Physical methods

In physical methods for biomass control, mechanical or hydraulic forces are used to remove biomass from medium beds.

Mechanical manipulation based on the use of mechanical forces has been proposed. One approach of mechanical manipulation to remove excess biomass is to mix the filter media to break up the compacted materials. Wübker et al. (1997) move biofilter bed periodically, and excess biomass are wasted from a BTF system with outflowing media. Rupert (1995) develops a biofilter in which a horizontal cylindrical vessel is installed and usually rotated several rotations a week so that biomass attached on the filter media can be broken up and removed periodically. Synthetic fiber or foam media constructed in biofilters at bench- or pilot-scale is more suitable for being squeezed repeatedly to remove excess biomass after being dismantled (Moe and Irvine, 2000; Moe and Qi, 2004). Yang et al.

(2004) remove excess biomass within sponge media of RDBs by repeatedly squeezing the sponge media in a nutrient solution periodically to maintain stable performance for the RDBs.

Backwashing of medium beds using water flow at a high flow rate periodically is also applied to remove excess biomass in biofilters. Smith et al. (1996) report that backwashing with medium fluidization at a bed expansion of about 40% for 1 h twice per week can successfully remove excess biomass from BTF systems. Kim et al. (2005) consider that backwashing is required to remove excess biomass accumulation in BTFs when VOC loading rate is larger than $3.52 \text{ kg COD m}^{-3} \text{ d}^{-1}$ (Kim et al., 2005). Kim and Sorial (2007) report that periodic backwashing at a rate of 1 h once a week are effective for the control of biomass accumulation in BTFs. Delhomenie et al. (2003) employ both bed stirring and bed washing to remove excess biofilms in a biofilter whose removal efficiency exceeds 80% for the treatment of toluene contaminated airs.

Methods including filling with water and draining, backwashing, and air sparging are evaluated to remove excess biomass from biofilter systems after long-term operation (Mendoza et al., 2004). The filling/drainage method which does not result in any biological inhibition to biofilter performance is the least efficient for biomass removal, and up to 5–10 times more biomass can be removed when temperature of the feeding water increased from 30 °C to 60 °C. Unfortunately, the effect of temperature on biofilter performances need more investigations due to the different removal efficiency of biomass in the experiments by backwashing with water and air sparging. Backwashing and air sparging lead to the similar performances on biomass removal. Periodical hydraulic backwashing of biofilter beds can more effectively remove excess biomass from biofilters and distribute biomass more evenly within biofilters, however, the consequent investment and operation cost of biofilter systems increase greatly.

Physical methods are effective for biomass control, however, the application of physical methods in biofilter systems at full-scale had been hindered due to some shortcomings including high energy consumption, auxiliary facilities, and complex operation.

3.2. Chemical methods

Controlling the feedings including carbon and nutrient sources and washing or filling with chemical solutions containing oxidants, surfactants, bactericidal and hydrolyzing compounds are classified into chemical methods for biomass control.

During a starvation period, carbon or nutrients in the incoming gas flow or liquid solution are not fed or fed much lower than normal feeding rates. According to the Liebig's law that one nutrient often determines the maximal biomass amount, starvation can control the growth and activity of biofilms by decreasing the relative concentrations of the one or more rate-limiting nutrients for a biofilter (Egli and Zinn, 2003).

Martin and Loehr (1996) evaluate the effect of starvation on biological activity and biomass amount in gas phase bioreactors. Cox and Deshusses (2002) report that loss of 10–50% of biomass is resulted when a biofilter lasts a period of 7 d of starvation. Kim et al. (2005) consider starvation is a feasible mean for biomass control when VOC loading ranges from 0.70 to $1.41 \text{ kg COD m}^{-3} \text{ d}^{-1}$. Kim and Sorial (2007) report a period of 2 d starvation for BTFs are effective for the control of biomass accumulation. The endogenous respiration rate of the biomass decrease exponentially during a starvation period of a biofilter (Metris et al., 2001). Potassium deficiency can reduce biomass accumulation rate while toluene elimination capacity increases with an increased rate of dilution (Wübker et al., 1997). Nitrogen can also be the rate limiting substance for biofilm growth in a BTF, however, excess biomass is still needed removing to keep stable high removal efficiency for extended duration of operation (Rihn et al., 1997).

After starvation, reacclimation time of hours to days is needed to recover initial removal efficiencies of a biofilter, and the exact period for reacclimation is dependent on both the starvation duration and the presence of alternative carbon source (Martin and Loehr, 1996). When toluene loading rate for a biofilter is increased after a starvation period, a significantly longer duration for reacclimation is required for the biofilter to achieve 99% removal efficiency (Kim et al., 2005). In a liquid phase bioreactor, the microorganisms readily biodegrade EPSs of themselves to supply maintenance energy and metabolization during a starvation period (Zhang and Bishop, 2003; Lobos et al., 2005). While in a BTF, the removal performance does not deteriorate when nutrients are deficiency, and toluene elimination capacity reaches $27 \text{ g Cm}^{-3} \text{ h}^{-1}$ when the biofilter is inoculated with fungi (Weber and Hartmans, 1996). Therefore, further investigations are needed to better understand the effect of nutrient deficiency during a starvation condition on biofilms and biofilter performance.

Washing filter beds with chemical solutions is an alternative to remove excess biomass in gas biofilters. Washing by NaOH solution decreases satisfactorily the net increase rate of biomass in a biofilter used for treatment of toluene contaminated waste gas streams, while high removal efficiency is maintained for a period of about 50 d of operation (Weber and Hartmans, 1996). Washing by solution of either NaOH or NaClO is effective to remove excess biomass in biofilters (Cox and Deshusses, 1999b; Xi et al., 2007). The use of 0.4% NaOH solution is more effective when NaOH solution is chosen (Xi et al., 2007), while the disadvantage of NaClO is the complete loss of activity of unremoved microorganisms (Cox and Deshusses, 1999b).

Washing biofilter medium bed with a chemical solution for biomass control often leads to a considerable drop of the biofilter performance immediately after the re-startup, and a period of up to several days is needed to reacclimate (Mendoza et al., 2004; Xi et al., 2007). Microorganisms in biofilms often need to tolerate a more harsh environment over a long period of operation in a chemical control method, so microbial activity of the biofilms can be decreased due to the toxicity or reaction of chemicals. Therefore, more investigations are needed to apply this approach to the operation of biofilters at full-scale.

3.3. Biological methods

There are shortcomings including higher cost and lower efficiency at the reacclimation period when physical or chemical methods are used for excess biomass control. Biological methods which can be cost-effective and environmentally friendly to control biomass accumulation are consequently paid close attention. Biological predation is considered as one of the most promising biological methods, and is on the basis of the ecological principles of ecological pyramids, trophic levels, and grazing food chains. Microbial populations among different trophic levels in a biofilter constitute the biomass pyramid. A longer food chain which consumes more energy leads to a lower yield of biomass, and the amount of biological species at lower trophic levels can be reduced under the presence of biological species at higher trophic levels in a biofilter. Battin et al. (2003) consider biofilms are highly efficient and successful ecological communities within which microbes contribute considerably to energy flow and nutrient cycling. Reducing sludge production through a grazing food chain has been employed by many researchers in wastewater treatment (Low and Chase, 1999; Wei et al., 2003). Ratsak et al. (1994) report biomass reduction and mineralization increase because of the grazing of ciliate tetrahymena pyriformis on pseudomonas fluorescens. Cech et al. (1994) describe the grazing of protozoa and metazoa on microorganisms in a SBR reactor. Dead cells can also be utilized as a food source for organisms at higher trophic levels such as protozoa, metazoa and nematodes. These results in wastewater treatment can be referred to the controlling of excess biomass in gas biofilters.

Up to now, the utilization of protozoan and metazoan predation for reducing biomass accumulation in gas phase biofilters is still at a preliminary stage. Cox and Deshusses (1999a) report that predation by protozoa can only reduce the biomass accumulation rate of about 10%–20% in a TFB, and it is still a challenge to maintain long-term stable performance. A slightly higher toluene elimination capacity and a lower rate of biomass accumulation are achieved in a suspended culture bioreactor aerated with toluene polluted air when there are protozoa (Cox et al., 1999). The introduction of mites can help control excessive fungal growth and reduce pressure drop in biofilters (van Groenestijn et al., 2001). Bhaskaran et al. (2008) compare some micro-metazoa including predatory nematodes (*Caenorhabditis* sp.), rotifers (*Philodina* sp.), tardigrades (*Echiniscus* sp.) and fly larvae with ciliate protozoa including *Colpoda inflata*, *Euplotes harpa* and *Acineria* sp., and results show that nematodes, rotifers and ciliates which can maintain a sustainable population are suitable for tolerating a wide range of pollutant concentration. Nevertheless, observation on biological predation with protozoa for control of clogging within biofilter beds is at an early stage. More researches on the performances and behaviors of protozoa and metazoa in grazing biofilms will be helpful.

In biofilm reactor systems, biological predation which may lead to some problems such as the decrease of bioreactor performance can also be copied with using other technologies such as a special alkaline backwash (Parker et al., 1997).

As a kind of unicellular animal, protozoa commonly can prey on organic granules or the microbes smaller than themselves, such as free bacteria. Most microorganisms including bacteria, however, exist in the form of biofilms or flocculent sludge clusters in gas phase biofilters. The clustered microorganisms, especially in biofilms, can resist the predation by protozoa. Meanwhile, protozoa introduced often disappear quickly in gas phase biofilters, which indicates that environmental conditions in biofilters usually do not favor the survival of the protozoa, especially when the target VOCs or pollutants are toxic to the protozoa (Cox and Deshusses, 1998). When metazoa or mixed species of protozoa and metazoa are used for the control of excess biomass accumulation in biofilters, the shortcomings of the use of protozoa for the control can be overcome or offset.

3.4. Improved biofilter designs

The period a biofilter can maintain a stable performance depends highly on the characteristics of packing media and on the operating conditions (Kennes and Veiga, 2002). Inert carriers, such as ceramic pellets (Alonso et al., 1997), vermiculites (Dupasquier et al., 2002) and polyurethane foams and sponges (Moe and Irvine, 2000; Yang et al., 2003a, 2008b), are widely used in gas biofiltration for better distributions of nutrients and biomass and for easier control of the operation conditions. Yang and Allen (2005) propose two design concepts to optimize biomass distribution and biofilter performance. One is a heterogeneous packing system in which larger particles is packed near gas inlet and smaller particles near gas outlet. The other applies a conical biofilter geometry which make the cross-sectional area of a biofilter change along the flowing direction of gas streams. A combined system consisting of a BTF, a denitrification reactor and a polishing bioreactor for the trickling liquid is developed for sustained treatment of ammonia while preventing biological inhibition by accumulating nitrite and avoiding generation of contaminated water (Sakuma et al., 2008).

Some innovative gas phase biofilters are also developed for the control of biomass accumulation and stably high removal performance. Cai et al. (2001) develop a gas phase biofilter packed with structured rotating carriers, and clogging of the packing can be avoided when used for styrene removal since spraying and jetting nozzles and an on-line quantification systems are installed to determine and remove attached biofilms within the media. Vinage and von Rohr (2003a,b) develop and evaluate a modified RBC for toluene removal from waste gas streams. In

the modified RBC, there is a hollow shaft on which 20 polypropylene discs are mounted. The modified RBC has maintained a stable toluene removal for more than one year during which biomass clogging has been successfully prevented. Three innovative types of RDBs including single layer, multi layer, and hybrid RDBs are developed using polyurethane sponge as packing media (Yang et al., 2003a,b, 2008b; Wang et al., 2006). The RDBs can distribute the VOC loadings and biofilm on the filter bed more evenly and improve the stability significantly even at high organic loading rates over a long period of operation (from about one month to six months or more) (Yang et al., 2004, 2008a). Biomass accumulation rates in a RDB are about 0.1 and 0.3 kg VSS per cubic meter of media per day at a toluene loading of 2.0 and 8.0 kg COD per cubic meter of media per day, respectively (Yang et al., 2003b), which are far lower than those in BTFs.

Some other bioreactors for waste gas treatment were also investigated, such as the conversion of full-scale wet scrubbers to BTFs for odorous pollutant removal at a municipal wastewater treatment plant at California (Gabriel et al., 2004) and suspended-growth bioreactor for the treatment of synthesized waste gas streams from a leather processing company (Carvalho et al., 2009). A novel gas-phase bioreactor, the foamed emulsion bioreactor (FEBR), has been developed and used for cometabolical biodegradation of trichloroethylene (TCE) with toluene by *Bukholderia cepacia* G4 (Kan and Deshusses, 2006). Buffer systems or buffering capacity have been integrated into bioreactor systems to prevent pollutant loading from fluctuating so that more stable performances are achieved (Li and Moe, 2005; Studer and von Rohr, 2008; Cai and Sorial, 2009). When operated under the reductive anaerobic conditions, a lab-scale BTF for TCE removal can reach more than 90% of TCE removal efficiency at loadings of up to $4 \text{ gm}_{\text{bed}}^{-3} \text{ h}^{-1}$ and sustained performance for over 200 days (Popat and Deshusses, 2009). These innovations help improve performances of gas phase biofilters.

Many innovations have been made in biofiltration. Yang (2004) proposes guidelines for RDB design and operation on the basis of biomass accumulation patterns. According to the guidelines, the dominant removal mechanism should be identified firstly on the basis of which the following procedures including the design criterion, medium configuration, biomass control strategy and operational parameter should be determined. Experiences and experimental results, however, are still critical for the design and operation of gas biofilters at full-scale up to now due to the complexity of biofiltration (Devinny and Ramesh, 2005).

3.5. Improved operation modes

Proper operation strategies can achieve a more even biomass distribution and a consequent more efficient use of the total medium bed and decrease the probability of medium clogging. Switching gas inlet position, splitting feeding gases, feeding intermittently, and equalizing VOC loads by adsorption prior to biofiltration are the main operation modes which help reduce biomass accumulation rate and avoid medium clogging.

In a DS mode, polluted air streams are fed alternatively through either the top or the bottom of a biofilter bed. Song and Kinney (2000) report that a biofilter operated in the DS mode at a 3-day interval achieves much more even biomass accumulation, higher activity of biofilms and lower pressure drop along the medium bed than another biofilter operated UD mode during a period of 96 days. It usually takes some time for a biofilter to reacclimate after a switch of feeding direction. Toluene elimination capacity for a biofilter in the DS mode is higher by about one time than that in the UD mode at a switching frequency of 12 h (Wright et al., 2005a). Pollutant elimination capacity is distributed more evenly along the bed depth of a biofilter when operated in the DS mode (Wright et al., 2005b).

Splitting feeding gas streams is a feasible strategy to reduce biomass accumulation rate in biofilters equipped with multiple feeding ports.

Comparing with conventional feeding mode, it can reach higher removal efficiency and more even distribution of biomass along the medium bed when an incoming waste gas stream is split into two flows with which the upper and middle inlets of the biofilter bed are separately fed (Mendoza et al., 2003).

Continuous feeding of VOCs at a high loading rate can result in an excess biomass accumulation in less than 20–30 days of operation, which can be avoided when using the intermittent feeding mode. Sempere et al. (2008) satisfactorily control biomass accumulation rate in a BTF in the intermittent feeding mode for a period of 75 d when the BTF is not fed with VOC loading at night and weekend. A biofilter in the intermittent feeding mode performs better for the treatment of waste gas streams with shock loading rates than that in the continuously feeding mode (Atoche and Moe, 2004).

Load equalization system prior to a biofilter is also used to buffer significant variations of inlet pollutant concentration, which may help control biomass accumulation and improve biomass distribution as mentioned above (Moe and Qi, 2005; Moe et al., 2007; Cai and Sorial, 2009). Li and Moe (2005) employ a granular activated carbon container before a gas phase biofilter to equalize transient and intermittent VOC loadings, which leads to an improved biofilter performance. Cai and Sorial (2009) use an adsorption bed to buffer the variation of organic loads to a BTF for the treatment of a mixture of toluene, styrene, methyl ethyl ketone (MEK), and methyl isobutyl ketone (MIBK), and the BTF achieve stable 99% removal efficiency at a loading rate less than $34.0 \text{ gm}^{-3} \text{ h}^{-1}$.

In summary, physical techniques are effective to remove most of biomass within biofilter media, while the investment and operating costs will increase. A long period of reacclimation may be needed when chemical methods are applied, and biological predation is considered as a promising technology. Biomass control by innovative biofilter designs and improved operation modes can lead to more evenly distribution of biomass dynamically and spatially, and consequently can control excess biomass accumulation in gas biofilters.

4. Conclusions

Biomass is critical to gas phase biofilter systems. Characteristics, compositions, and structure of constructed biofilms in gas phase biofilters can be similar to that of natural biofilms. Analytical and research methods for both natural biofilms and for biofilms in water treatment facilities can be referred in investigations on biofilms in gas phase biofilters.

Uneven biomass distribution and excess biomass accumulation are among the most difficult problems for gas phase biofilters at full-scale, and severe problems including the clogging of biofilter bed, great pressure drop, flow channeling, and consequent rapid deterioration of biofilter performance can be resulted in. There exist different biomass accumulation patterns which may represent removal mechanisms in gas phase biofilters. Understanding the mechanisms of biomass accumulation helps overcome these problems, and process modeling is an effective tool to better understand biomass accumulation mechanisms.

Methods of the control of excess biomass accumulation in gas biofilters can be categorized into physical techniques, chemical methods, biological predation, innovative biofilter designs, and improved operation modes. Each of these five types of biomass control strategies has its advantages and disadvantages to maintain stable biofilter performances, and simultaneous application of more than one type of these biomass control strategies can be more effective.

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