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REVIEW

Biofilter in Water and Wastewater Treatment

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Abstract−Biofilter is one of the most important separation processes that can be employed to remove organic pollutants from air, water, and wastewater. Even though, it has been used over a century, it is still difficult to explain theoretically all the biological processes occurring in a biofilter. In this paper, the fundamental of biological processes involved in the biofilter is critically reviewed together with the mathematical modeling approach. The important operating and design parameters are discussed in detail with the typical values used for different applications. The most important parameter which governs this process is the biomass attached to the medium. The relative merits of different methods adopted in the measurement of the biomass are discussed. The laboratory-and full-scale applications of the biofilter in water and wastewater treatment are also presented. Their performances in terms of specific pollutant removal are highlighted.

Key words: Biofilter, Biomass, Organics, Water, Wastewater

INTRODUCTION

Filtration is one of the most important treatment processes used in water and wastewater treatment. In water treatment, it is used to purify the surface water for potable use whereas in wastewater treatment, the main purpose of filtration is to produce effluent of high quality so that it can be reused for various purposes. Any type of filter with attached biomass on the filter-media can be defined as a biofilter. It can be the trickling filter in the wastewater treatment plant, or horizontal rock filter in a polluted stream, or granular activated carbon (GAC) or sand filter in water treatment plant. Biofilter has been successfully used for air, water, and wastewater treatment. It was first introduced in England in 1893 as a trickling filter in wastewater treatment [Metcalf and Eddy, 1991], and since then, it has been successfully used for the treatment of domestic and industrial wastewater. Originally, biofilter was developed using rock or slag as filter media, however at present, several types and shapes of plastic media are also used. There are a number of small package treatment plants with different brand names currently available in the market in which different shaped plastic materials are packed as filter media and are mainly used for treating small amount of wastewater (e.g. from household or hotel). Irrespective of its different names usually given based on operational mode, the basic principle in a biofilter is the same: biodegradations of pollutants by the micro-organisms attached onto the filter media.

Use of a biofilter in drinking water treatment (especially with granular activated carbon as filter media) was felt necessary only after the discovery of the re-growth of micro-organisms in water distribution pipe lines few decades ago. It has been observed that the inner surface of water distribution pipelines carrying potable water is coated with layers of biomass in few years of service period [Van der Kooij et al., 1982; LeChevallier and Lowry, 1990; Bouwer and Crowe, 1988]. The biodegradable organic matter (BOM), NH_4^+, Fe^{2+}, Mn^{2+}, NO_2^-, dissolved H_2 and several other reduced species of sulfur are the most pertinent components that can cause bacterial regrowth on the water distribution pipelines [Rittmann and Huck, 1989]. Due to the “regrowth” of the microbial mass in the pipelines, the drinking water is considered biologically not stable. Even though there is no direct evidence of its instant health and hazardous side effects, use of such drinking water in long run cannot be assured to be safe. Besides the by-products of chlorine disinfection, disinfections by-products (DBPs) are often carcinogenic and harmful. The biological treatment especially by granular activated carbon (GAC) biofilter has been found effective in removing organic substances that can cause the microbial growth in the pipe lines, and is normally recommended to be included in the water treatment processes after ozonation [Bouwer and Crowe, 1988; Hozalski et al., 1995; Ahmad and Amirtharajah, 1998; Carlson and Amy, 1998]. Bacterial masses attached onto the filter media as biofilm oxidize most of the organics and use it as an energy supply and carbon source. Removal of the organic matters not only impairs microbial regrowth but also reduces taste and odor, the amount of organic precursor (available to form disinfection by-products, corrosion potential) and other micropollutants of health and aesthetic concern.

Because of its wide range of application, many studies have been done on biofiltration system in last few decades (Table 1). However, theoretically it is still difficult to explain the behavior of a biofilter. The growth of different types of microorganisms in different working conditions makes it impossible to generalize the microbial activities in a biofilter. The biofilters operated at different filtration rates and influent characteristics can have diverse efficiency for different target pollutants. Besides, due to some of the operational drawbacks of the biofilter such as performance fluctuation, maintenance of biomass, and disinfection adequacy of the biofilter effluent, research on biofiltration process has become imperative.

This paper mainly focuses on the theoretical and modeling aspects, and the performance of the biofilter in removing organics,

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Table 1. Summary of the past studies on biofiltration system with water and wastewater

Researcher, source	Filter medium	Experimental parameter		Major observation
		Organic	Biomass	
Ahmad et al. [1998], water	Anthracite+sand	AOC-P17, AOC-NOX, NPOC, turbidity	HPC	Backwashing technique and hydraulic transient can affect the performance of a biofilter.
Boon et al. [1997], wastewater	Granite, blast-furnace slag	BOD, ammonia, SS	None	Performance a biofilter depends on organic load ing rate, temperature, and filter design configuration.
Carlson and Amy [1998], water	Anthracite	DOC, BDOC	Phospholipid analysis	DOC removal is controlled by biomass. The filter acclimatized at higher HLR had a substantially higher cumulative biomass.
Hozalski and Bouwer [1998], synthetic water, NOM	Glass beads+sand	TOC	HPC bacterial count	Biomass accumulation is not impaired by backwash with water
Yang et al. [2001], aquaculture water	Plastic media-3 different shapes	BOD$_5$, SS, NH$_3$-N, NO$_3$-N, NO$_2$-N, PO$_4^{-3}$	None	Characteristics of filter media are more critical than the flow scheme to the biofilter in affecting the performance of the biofilter.
Niquette et al. [1998], water	GAC	DOC, DO, NH$_3$, NO$_2$	Bacterial count	Shut down of biofilter promotes anaerobic conditions reducing the quality of the effluent. The biofilter should be backwashed when anaerobic condition occurs.
Servais et al. [1994], water	GAC	DOC, BDOC, NBDOC	^{14}C-Glucose respiration	Removal efficiency of a biofilter depends on EBCT, not on filtration rate
Wang et al. [1995a, b]	Anthracite+sand, GAC+sand, sand	TOC, BDOC, aldehydes, AOC-NOX, THM and TOX formation potential	Phospholipid analysis	GAC contained 3-8 times more biomass than anthracite or sand

AOC=Assimilable organic carbon, BOD$_5$=Biochemical oxygen demand, SS=suspended solid, DBP=Disinfection by-product, DOC=Dissolved organic carbon, DO=Dissolved oxygen, BDOC=Biodegradable dissolved organic carbon, NBDOC=Non-biodegradable dissolved organic carbon, THMFP=Trihalomethane formation potential, TOXFP=Total organic halide formation potential, HPC=Heterotrophic plate count, NPOC=Non-purgeable organic carbon, HLR=hydraulic loading rate, NOX=Nitrogen oxides.

nutrients, and some specific pollutants from water and wastewater.

THEORETICAL BACKGROUND

1. Fundamentals of Biological Process

In a biofiltration system, the pollutants are removed due to biological degradation rather than physical straining as is the case in normal filter. With the progression of filtration process, microorganisms (aerobic, anaerobic, and facultative bacteria; fungi; algae; and protozoa) are gradually developed on the surface of the filter media and form a biological film or slime layer known as biofilm. The development of biofilm may take few days or months depending on the influent organic concentration. The crucial point for the successful operation of a biofilter is to control and maintain a healthy biomass on the surface of the filter. Since the performance of the biofilter largely depends on the microbial activities, a constant source of substrates (organic substance and nutrients) is required for its consistent and effective operation.

There are three main biological processes that can occur in a biofilter, (i) attachment of microorganism, (ii) growth of microorganism and (iii) decay and detachment of microorganisms. As the success of a biofilter depends on the growth and maintenance of microorganisms (biomass) on the surface of filter media, it is necessary to understand the mechanisms of attachment, growth and detachment on the surface of the filter media.

1-1. Attachment of Microorganisms

The mechanisms by which microorganisms can attach and colonize on the surface of the filter media of a biofilter are (i) transportation, (ii) initial adhesion, (iii) firm attachment, and (iv) colonization [Van Loosdrecht et al., 1990]. The transportation of microorganisms to the surface of the filter media is further controlled by four main processes, (a) diffusion (Brownian motion), (b) convection, (c) sedimentation due to gravity, and (d) active mobility of the microorganisms. As soon as the microorganisms reach the surface, initial adhesion occurs which can be reversible or irreversible depending upon the total interaction energy, which is the sum of Van der waals force and electrostatic force. The DLVO (Derjaguin-Landau-Verwey-Overbeek) theory is often used to describe the adhesion of the microorganisms on the surface of the filter media. The processes of firm attachment and colonization of microorganisms depend on influent characteristics (such as organic type and concentration) and surface properties of the filter media. The steric effects, hydrophobicity of the microorganisms, contact angle, and electrophoretic mobility values are taken into consideration to estimate the attachment of microorganisms on the surface of filter media.

1-2. Substrate Utilization and Biomass Growth

A biofilm is an accumulation of microorganism onto a surface. Since the microorganisms are attached to the surface, the supply of organics or substrate (food) to the microorganisms in a biofilm is mainly controlled by the bulk and surface transport phenomena. The substrate must be transported from the bulk liquid to the biofilms outer surface where it has to diffuse into the biofilm for its metabolism. The factors that influence the rate of substrate utilization within a biofilm are (i) substrate mass transport to the biofilm, (ii) diffusion of the substrate into the biofilm, and (iii) utilization kinetics within the biofilm. The other key factors that affect the performance of a biofilm process are the growth yield of the substrate and the physical factors affecting the biofilm detachment.

The substrate transport from the bulk liquid to the outer surface of the biofilm can be described by Fick's first law [Eq. (1)]:

$$\mathrm{J}=\frac{\mathrm{AD}(\mathrm{S}-\mathrm{S}_s)}{\mathrm{L}_d} \tag{1}$$

The substrate transport to the microorganism inside the biofilm by molecular diffusion can be described by Fick's second law [Eq. (2)] and the substrate utilization by the Monod expression [Eq. (3)].

$$\mathrm{r}_d=\mathrm{D}_f\frac{\partial^2\mathrm{S}_b}{\partial\mathrm{Z}^2} \tag{2}$$

$$\mathrm{r}_u=\frac{\mathrm{kX}_f\mathrm{S}_b}{\mathrm{K}_s+\mathrm{S}_b} \tag{3}$$

The factors that can affect the growth of biomass in non-steady state conditions are given by Eq. (4) [Rittmann and Brunner, 1984].

$$\mathrm{r}_g=\frac{\mathrm{YkX}_f\mathrm{S}_b}{\mathrm{K}_s+\mathrm{S}_b}\mathrm{A}_f\mathrm{L}_f \tag{4}$$

1-3. Detachment of Biomass

The success of a biofilter mainly depends on the efficient maintenance of biomass attached to the filter media. Biomass detachment is one of the most important mechanisms that can affect the maintenance of biomass in a biofilter. Erosion, abrasion, sloughing, grazing or predation, and filter backwashing are the mostly observed and literally discussed detachment mechanisms. Erosion of biomass occurs due to the fluid shear whereas abrasion of biomass is the process of scraping the biocell off the surface by collision of external particle. Similarly, large patches of biomass are detached by sloughing, and a part of biomass especially on the outer surface of the biofilm may be lost due to the grazing of protozoa. Evaluation of the biomass loss due to filter backwashing is very important in operational point of view. Backwash bed expansion, mode of backwash such as air scour, filter effluent or chlorinated water backwash may affect biomass during backwashing. However, previous studies have shown that the effective biomass which is mainly responsible for the organic removal is not lost during normal filter backwash [Chaudhary et al., 2001; Ahmad and Amirtharajah, 1998]. Most of studies have been concentrated on biomass loss due to shear stress only. A summary of the reported biomass loss due to shear stress in GAC biofilter is presented in Table 2.

Table 2. Detachment rate expressions (adopted from Hozalski, 1996)

Detachment rate $[\mathrm{ML}^{-2}\mathrm{T}^{-1}]$	Reference
$\mathrm{k}_d\cdot\mathrm{X}_f\cdot\mathrm{L}_f$	Chang and Rittmann [1987], Rittmann [1989]
$\mathrm{k}_d\cdot\mathrm{X}_f\cdot(\mathrm{L}_f)^2$	Wanner and Gujer [1986]
$\mathrm{k}_d\cdot\mathrm{X}_f\cdot\tau$	Bakke et al. [1990]
$\mathrm{k}_d\cdot\mathrm{X}_f\cdot\mathrm{L}_f\cdot\tau^{0.58}$	Rittmann [1982]
$\mathrm{L}_f\cdot(\mathrm{k}_d^{/}+\mathrm{k}_d^{//}\cdot\mu_g)$	Speitel and DiGiano [1987]
$\mathrm{k}_d\cdot\mu_{gave}\cdot\mathrm{X}_f\cdot(\mathrm{L}_f)^2$	Peyton and Characklis [1992]

2. Mathematical Modeling

There are very few models reported in the literature that can predict the performance of a biofilter. Most of these models are based on the assumption of steady state condition [Rittmann, 1990; Rittmann and Manem, 1992; DiGiano and Speitel, 1993]. Rittmann and McCarty [1980] first introduced a steady-state biofilm model in which, the mass transport and the microbial kinetics were expressed by Fick's second law and Monod equation respectively. It was assumed that minimum bulk substrate concentration (S_{min}) is required to maintain the steady-state biofilm in the filter. The model describes the fundamental biological processes but does not take into account the biofilm growth with time.

Chang and Rittmann [1987] developed a model for the kinetics of biofilm on activated carbon (BFAC) incorporating film mass transfer, biodegradation, and adsorption of a substrate, as well as biofilm growth. All the fundamental biological processes have been included in this model. However, the non-steady state condition due to backwashing, change in the filter bed porosity and hence the filter depth have not been considered in this model.

The concept of dimensionless empty bed contact time (EBCT), which allows comparison of results among different surrogate parameters such as AOC and BDOC (Biodegradable dissolved organic carbon) was developed by Zhang and Huck [1996a] utilizing the steady-state biofilm model of Rittmann and MaCarty [1980]. Huck et al. [1994] developed a first order biofilm model. The model is more practical than accurate in predicting the performance of a biofilter. It assumes that the organic removal in a biofilter is directly proportional to the influent concentration.

Billen et al. [1992] developed the CHABROL model to predict BDOC removal. The model incorporates the major microbial processes and substrates of different biodegradabilities. The model showed that BDOC removal is directly proportional to influent BDOC and EBCT. The three kinds of interaction, (i) interaction with dissolved organic matter, (ii) interaction with the solid support, and (iii) the mortality and grazing of bacteria have been incorporated in the model to describe the dynamics of the bacterial community colonizing on the support (filter media). The model consists of six state variables, namely: concentrations of rapidly and slowly hydrolysable biodegradable macromolecules of organic substances, concentrations of directly usable monomeric substances, bacterial biomass actively attached to the solid support, the bacterial biomass reversibly adsorbed to the support, and free bacterial biomass in interstitial water.

The model is capable of relating the macroscopic functioning of biofilters to the kinetics of the basic microbiological processes. It can predict the fixed bacterial biomass and the biodegradable organic matter in the effluent from the characteristics of influent water for a given values of contact time and temperature. The model was also calibrated and validated with pilot and full size filters run in the Neuilly-sur-Marne and Choisy-le-Roi plants, France.

Most of the above-mentioned models describe the biological processes in a biofilter. There are no complete models that can predict the efficiency of the biofilter at different operating conditions. Boon et al. [1997] conducted pilot-scale biofilter experiments with sewage and developed empirical equations to predict the biochemical oxygen demand (BOD_5) and ammonia removal by the biofilters. It was observed that organic and hydraulic loading rates of the biofilter can limit the organic removal efficiency of the biofilter.

Hozalski and Bouwer [2001a] developed a numerical model called BIOFILT, to simulate the non-steady state behavior of biologically active filters used for drinking water treatment. The model is capable of simulating substrate (biodegradable organic matter) and biomass (both attached and suspended) profiles in a biofilter as a function of time. The model also has capability to simulate the effects of a sudden loss in attached biomass due to filter backwash on substrate removal efficiency [Hozalski and Bouwer, 2001b]. The model is very practical and it incorporates most of the fundamental processes of the biofiltration. Some of the limitations reported on this model are: (i) It is a single substrate model, (ii) It assumes that there is no mixing of the filter media during backwashing, (iii) It does not incorporate the adsorption of substrate that occurs when GAC is the filter media of the biofilter, and (iv) The model requires data on parameters to perform the simulation.

Despite these limitations, the BIOFILT is the first model that incorporates the backwashing effect in the simulation, and should be considered as the most practical model to date. The simulated results of different fractions of a BOM mixture in a full-scale biofilter plant are shown in Fig. 1.

Although, all the models described above are successful in modeling the fundamental biological processes of a biofilter, the other important parameters that need to be addressed in the biofilter model are change in: (i) filter bed porosity, (ii) surface area, and (iii) bed depth. The model should be able to predict the long-term performance of the biofilter at different operating conditions such as organic and hydraulic loadings changes. Alonso et al. [2001] developed a dynamic mathematical model for the biodegradation process of volatile organic compounds (VOCs) using diatomaceous earth biological support media (Celite 6 mm R-635 Bio-Catalyst Carrier). The effect of nitrate concentration, reactor backwashing, and change in bed porosity and specific surface area of the filter media have been incorporated in the model.

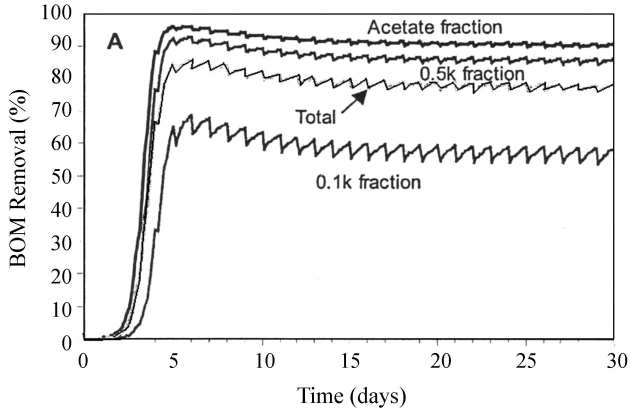

Fig. 1. Simulated removal of different fractions of a BOM mixture in a full-scale biofilter [Hozalski and Bouwer, 2001a].

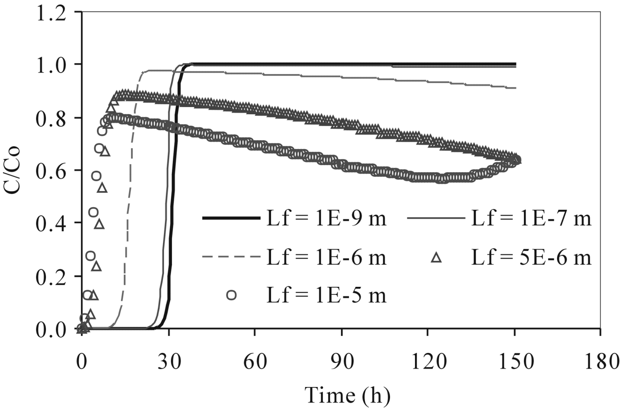

Fig. 2. Effect of biofilm thickness on simulation results [Chaudhary, 2003].

Chaudhary [2003] modeled the long-term performance of a GAC biofilter with low strength synthetic wastewater incorporating both initial adsorption and biodegradation processes. The model was based on the fundamental mechanisms of transport of substrate in the bulk liquid, biofilm growth, transport, and biodegradation within the biofilm, and adsorption on activated carbon. The effect of biofilm thickness on simulation n results is shown in Fig. 2.

2-1. Description of State Variables

The main components that need to be incorporated in the model are: (i) substrate in the liquid bulk liquid, (ii) biomass suspended in the bulk liquid, (iii) substance diffusion and biodegradation in biofilm, (iv) biofilm growth and decay, and (v) change in bed porosity, specific surface area and bed depth.

2-1-1. Substrate in the Bulk Liquid

The unsteady-state material balance on the substrate in the bulk liquid is represented by the advection-diffusion equation with adsorption and reaction terms [Eq. (5)]

$$\frac{\partial C}{\partial t}=D_{ax}\cdot\frac{\partial^2 C}{\partial z^2}-v\cdot\frac{\partial C}{\partial z}-\gamma_{bio}-\gamma_{ads} \tag{5}$$

with initial and boundary conditions

$$\begin{aligned} &C=C_0\\ &D_{ax}\frac{dC}{dz}=-v\cdot(C|_{z=0^-}-C|_{z=0^+})\ \text{at}\ z=0\\ &\frac{dC}{dz}=0\ \text{at}\ z=L \end{aligned} \tag{5a}$$

The last two terms of the Eq. (5) represent the substrate removal rates by biodegradation and adsorption respectively, and are given by:

$$\gamma_{bio}=k_{max}\cdot\frac{C}{K_s+C}\cdot X_s \tag{5b}$$

$$\gamma_{ads}=(1-\varepsilon)\cdot\frac{3N}{4\cdot\pi\cdot R_p^3} \tag{5c}$$

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2-1-2. Biomass Suspended in the Bulk Liquid

The suspended biomass in the bulk liquid can be represented by

Eq. (6).

$$\frac{\partial X_s}{\partial t}=\left(Y\cdot\frac{k_{max}\cdot C}{K_s+C}-K_{dc}-\frac{\beta}{\theta\cdot\varepsilon}\right)\cdot X_s+\frac{1-\varepsilon'}{\varepsilon'}\cdot a'_f\cdot X_f\cdot\sigma \tag{6}$$

with initial and boundary conditions,

$$X_s=X_{s0} \text{ and } z=0 \tag{6a}$$

2-1-3. Biofilm Diffusion and Biodegradation

Biofilm diffusion and biodegradation of the substrate is given by Eq. (7).

$$\frac{\partial S_b}{\partial t}=D_f\cdot\frac{\partial^2 S_b}{\partial x^2}-X_f\cdot\frac{k_{max}\cdot S_b}{K_s+S_b} \tag{7}$$

It is assumed that the substrate diffuses through biofilm where it is biodegraded by the microorganisms.

2-1-4. Biofilm Growth and Decay

Since the biofilm growth rate is directly related to the biological activity, the cell growth rate (which is the sum of the cell production rate due to degradation and its decay rate) can be written as in Eq. (8).

$$\frac{dL_f}{dt}=\int_0^{L_f}\left(\frac{Y\cdot k_{max}\cdot S}{K_s+S}-b_{tot}\right)\cdot dr \tag{8}$$

2-1-5. Change in Bed Porosity, Specific Surface Area and Bed Depth

The growth of biofilm in the bed alters the bed porosity, the specific surface area, and the filter medium depth as the bioadsorption proceeds. These changes are given by the Eqs. (9), (10), and (11) respectively.

$$\varepsilon'=1-(1-\varepsilon_0)\cdot\left[\left(1+\frac{L_f}{R_p}\right)^3-\frac{n}{4}\cdot\left(\frac{L_f}{R_p}\right)^2\cdot\left(2\frac{L_f}{R_p}+3\right)\right] \tag{9}$$

$$a'_f=\frac{3(1-\varepsilon_0)}{2\cdot R_p}\cdot\left(1+\frac{L_f}{R_p}\right)\cdot\left[(2-n)\cdot\frac{L_f}{R_p}+2\right] \tag{10}$$

$$\frac{L}{L_0}=\left(\frac{1-\varepsilon_0}{1-\varepsilon'}\right)\cdot\left[\left(1+\frac{L_f}{R_p}\right)^3-\frac{n}{4}\cdot\left(\frac{L_f}{R_p}\right)^2\cdot\left(2\frac{L_f}{R_p}+3\right)\right] \tag{11}$$

DESIGN CONSIDERATION

The parameters that can affect the performance of a biofilter are the characteristics of filter media, hydraulic and organic loading rate, and filter backwash techniques. Other factors that can influence the performance of a biofilter are the temperature and the presence of oxidants, i.e. O_3, H_2O_2, Cl_2, and NH_4Cl etc. in the influent [Urfer et al., 1997; Goel et al., 1995]. These factors should be carefully studied before designing a biofiltration system.

1. Filter Media

The economical and efficient operation of a biofilter highly depends on the characteristics of its filter media. While selecting the filter media, one should also consider the source and concentration of targeted pollutants. For the treatment of primary wastewater, the right choice of the filter media can be the blast furnace slag or granite or synthetic media depending upon the volume of wastewater, whereas for the treatment of tertiary wastewater, air stream containing VOCs or for removing offensive organic substances from the drinking water supply line, GAC or anthracite or filter coal or sand could be the better choice. Previous studies have shown that GAC (an adsorptive media) can be a better choice than anthracite or sand (non-adsorptive media) for the removal of organic substances from tertiary wastewater or surface water [LeChevallier et al., 1992; Wang et al., 1995a, b]. A GAC filter might have less specific surface area (surface area per unit volume of filter) available for microbial attachment than a sand filter because the effective size of sand is usually smaller than GAC. Further the size of GAC micropores (1-100 nm) seem to be too small for microorganisms (typically greater than 200 nm in diameter) penetration inside these micropores (AWWA research and technical committee report, 1981). However, the macroporous structure and irregular surface of GAC offer more appropriate sites for biomass attachment. GAC can adsorb and retain slowly biodegradable components that can be biodegraded by the attached microbial mass leading to continuous bioregeneration of the GAC. It also provides protection from shear loss of biomass. Wang et al. [1995a] found the mesoporous GAC surface texture more suitable for biomass attachment than macroporous and microporous GAC.

The biofilter media should provide: (i) a suitable surface for quick biomass growth, (ii) larger surface area for biomass growth, and (iii) good surface texture to hold biomass against shear and sloughing. The effect of types of media on the performance of the biofilter is shown in Fig. 3.

2. Empty Bed Contact Time (EBCT)

The contact time, usually expressed as empty bed contact time (EBCT), is a key design and operating parameter of a biofilter. Zhang and Huck [1996b] have introduced the concept of dimensionless contact time incorporating EBCT, specific surface area of the medium, substrate diffusivity and rate of biodegradation. Usually the percentage removal of organic substances increases with increase in contact time up to an optimum value. Both the filter depth and hydraulic loading can be changed to increase the EBCT. Previous studies have shown that the contact time (and not the hydraulic loading) is the key variable responsible for organic removal. For a given EBCT, organic removal is independent of hydraulic loading in the range typically used in rapid filtration [Servais et al., 1994; Carlson

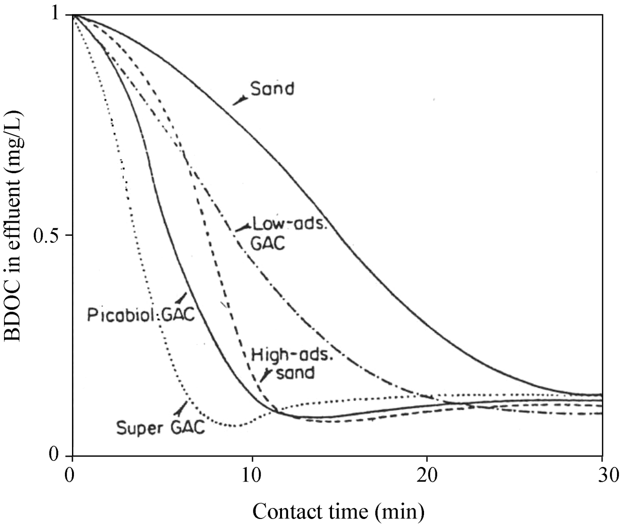

Fig. 3. Effect of types of filter media on the performance of biofilter [Billen et al., 1992].

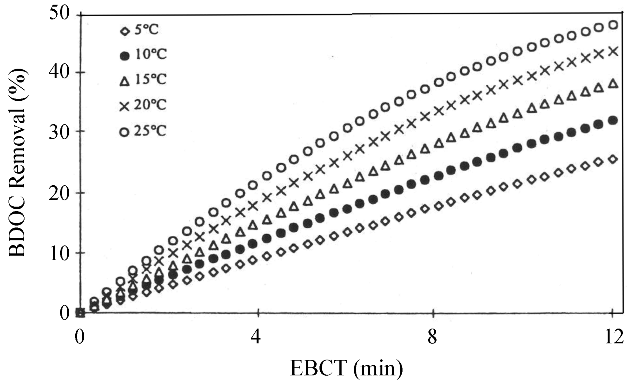

Fig. 4. Effect of EBCT on the performance of biofilter (Chabrol model) [Laurent et al., 1999].

and Amy, 1995]. Huck et al. [1994] showed that the organic removal efficiency of a biofilter could be approximated by a first-order model. Servais et al. [1992] reported a linear increase in BDOC removal with the increase in EBCT between 10-30 min of the biofilter. The past studies [Price, 1994; Hozalski et al., 1995], which showed very little or no effect of EBCT on organic removal efficiency of a biofilter, might be due to partial acclimatization of the biofilter. The effect of EBCT on the performance of biofitler is shown in Fig. 4.

3. Filter Backwash

It is important to select an appropriate filter backwashing technique for successful operation of a biofilter. The biomass attached to the filter media has to be carefully maintained during backwashing [Ahmad et al., 1998; Bouwer and Crowe, 1998; Bablon et al., 1988; Graese et al., 1987; Miltner et al., 1995]. Ahmad and Amirtharajah [1998] found that biological particles (measured as heterotrophic plate counts and cellular adenosine triphosphate), which are usually hydrophobic in nature, are attached to filter media (GAC) with a greater force than non-biological clay particle (measured as turbidity). The difference in the detachment of these particles during backwashing should be taken into account while selecting or optimizing the backwashing of a biofilter. Previous researches have shown no major loss of biomass during backwash of the biofilter [Ahmad et al., 1998; Lu and Huck, 1993]. Servais et al. [1991] backwashed the GAC biofilter with air scour and water routinely every 50-100 hours of continuous run, but no significant difference in vertical biomass profiles before and after backwash was observed.

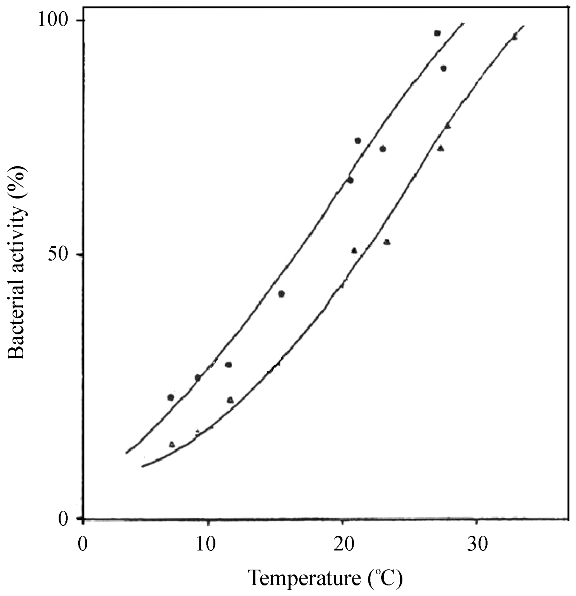

Fig. 5. Percentage of bacterial activity with respect to maximal activity with respect to temperature [bacterial community adapted at 10 °C (●) and 20 °C (△)] [Billen et al., 1992].

4. Temperature

The effect of temperature on the bacterial activity on the biofilter and hence the performance of the biofilter is shown in Fig. 5. The activities of bacterial community adapted at 10 °C and 20 °C were found to increase with increase in temperature in range of 10-30 °C.

BIOFILTER STATE VARIABLE PARAMETERS AND THEIR MEASUREMENT

1. Substrate

Biofilters are used for many purposes. It can be used for the treatment of primary wastewater, tertiary wastewater or for the treatment of potable water. Measurement of biofilter state variable parameters depends on the purpose of the use of the biofilter. If the purpose of the biofilter is to treat the primary wastewater, then the parameters that should be measured are BOD, COD, SS etc. However, when the biofilter is used for the tertiary wastewater treatment, then the organic level such as TOC could be an appropriate parameter to be measured. Similarly, the main purpose of the use of a biofilter in potable water treatment is to reduce the chlorine demand or disinfection by-product formation potential and the bacterial re-growth potential, and its measurements are expressed in terms of BDOC and AOC. Since the measurement of AOC or BDOC is of specific nature, precise measurement methods are required. Some of the commonly used methods for the measurement of AOC and BDOC as reported by Huck [1990] are: (a) Van der Kooij method, (b) Kemmy method, (c) US-EPA method, (d) Werner method, (e) Jago-Stanfield method, and (f) Billen-Servais method. In Van der Kooij method, the AOC concentration is expressed as μg acetate C eq/L, whereas in Kemmy and US-EPA methods, colony-forming units (cfc/ml) is measured and then converted into AOC μg/L and coliform growth response (CGR) respectively. In Werner and Jago-stanfield methods, the bacterial cell concentration is measured in terms of turbidity or adenosine triphosphate (ATP) concentration. Billen-Servais method measures the biodegradable dissolved organic carbon (BDOC).

2. Biomass Growth

The performance of a biofilter depends on the biomass attached to the filter media. The biomass growth and its maintenance over the surface of the filter media, on the other hand, depend mostly on the surface characteristics of the filter media itself. As mentioned earlier, different media can have different biomass growth rate and biomass retention capacity. GAC, sand, anthracite, blast-furnace slag and floating polypropylene pellets are some of the common biofilter media used in the water and wastewater treatment. Other factors that can affect the biomass accumulation are the filtration rate, filter backwashing techniques, and the organic content of the influent wastewater. Most of the studies with natural surface water showed that 3-months period is required for a GAC filter to retain maximum amount of biomass [Servais et al., 1994; Ahmad and Amirtharajah, 1998].

Several methods are adopted in practice to measure the biomass attached to the filter media depending on the availability of the analytical facilities. Usually for the biofilter used in water treatment facilities, the amount of biomass is relatively small (in microgram) and hence precise methodology for the biomass measurement is required.

Ahmad et al. [1998] however, used heterotrophic plate count (HPC) to measure the biomass growth in the biofilter. The heterotrophic bacteria were enumerated by using the spread plate method according to the STANDARD METHODS [1989] section 9215C. The growth medium used was R2A agar, and incubation conditions were 20 °C for seven days.

Wang et al. [1995a] used phospholipids analysis to estimate the biomass in the biofilter. About 0.5 g of GAC filter media with attached biomass were taken from the filter, and washed with dechlorinated tap water to remove the suspended solids so that the measured mass would be only the attached biomass. Basically, the method is to extract the organically bound phosphorous and then it is digested to inorganic phosphate which can be quantified by colorimetric measurement. The amount of biomass is reported as nmol lipid-P/g dry filter media (1 nmol lipid-P is equivalent to about 10^8 bacteria of the size of *E.coli*).

Servais et al. [1994] suggested that it would not be possible to enumerate the bacteria attached onto activated carbon due to size and surface irregularity of the GAC, and developed a new approach to estimate the bacterial biomass. In this method, bacterial activity is measured under standard conditions, and then it is related to size of active bacterial population through the glucose the respiration rate, and finally correlated to µg C of biomass by a conversion factor of 1.1 µg C of bacterial biomass per nanomole of glucose respired per hour [Servais et al., 1991].

Chaudhary et al. [2001] used total dry weight method to measure the biomass in a GAC biofilter acclimatized with synthetic wastewater (Fig. 6). This method is simple and more practical to measure the biomass of relatively large quantity. Maximum biomass measured was 0.09 g per g of GAC after 42 days of operation. A minimum biomass concentration of 0.036 g per g of GAC was observed after 63 days of continuous operation. Another set of experiments conducted with filtration rate of 2.5 m/h showed a biomass concentration of 0.1 g per g of GAC in 30 days of continuous filter run. The amount of biomass accumulation thus found to be dependent on hydraulic loading rate (HLR) and the organic concentration.

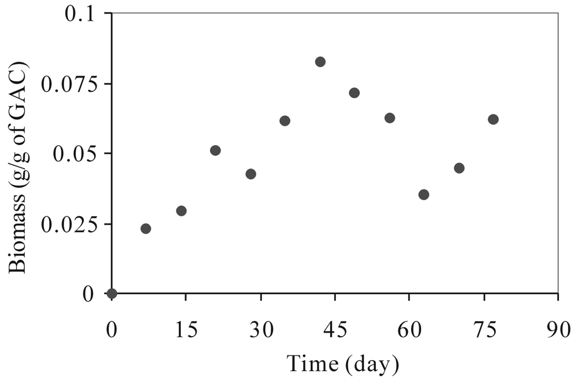

Fig. 6. Biomass accumulations in the GAC biofilter (Filtration rate =1 m/h, average influent TOC=3.5 mg/L) [Chaudhary et al., 2001].

Carlson and Amy [1998] also found the biomass concentration profile as a function of HLR. The higher the loading rate, the greater was the initial biomass and deeper the penetration into the filter bed. The biomass concentration profile thus appears to be the most critical parameter in the design of biofiltration system.

Two important changes that can be observed due to the biomass coating on the outer surface of the GAC pellet are: (i) a decrease in the fixed bed porosity, and (ii) an expansion of the GAC bed of the biofilter. The maximum bed expansion of 1.14 cm (equivalent to 22.8% expansion) was observed by Chaudhary et al. [2001] after 42 days operation.

A study of GAC biofilter at Neuilly-sur-Marne water treatment plant, France [Servais et al., 1994] showed that for a given empty bed contact time (EBCT), biological removal of organic matter in GAC filters is independent of filtration rate in the range of 6-18 m/h. They also found some decrease in biomass after 100 days of operation. However, the average biomass in the filter operating at different filtration rates but at identical contact times remained almost constant.

Ong et al. [1999] working with high strength wastewater (BOD_5= 389 mg/L) in an ultra-compact biofilm reactor observed 52.5% and 32.8% decrease in biomass after 38 days and 94 days of filter run respectively. The decrease in biomass in the biofilter may be due to die-off of microorganisms and its subsequent removal during backwashing. Despite the decrease in the biomass, the removal efficiency of the biofilter is not impaired, and it continues to produce consistent quality of effluent [Chaudhary et al., 2001; Ahmad et al., 1998].

APPLICATION OF BIOFILTER

Biofilter can be employed either as a primary treatment unit or secondary unit in the wastewater treatment system. When the amount of wastewater is relatively small and hence a complete treatment can be accomplished in one tank (package treatment plant) which has been partitioned for pretreatment, biofiltration, and sedimentation processes (Fig. 7). Various types and shapes of plastic materials are used as the biofilter media. This type of package treatment plant is widely used to treat on-site household and industrial waste-

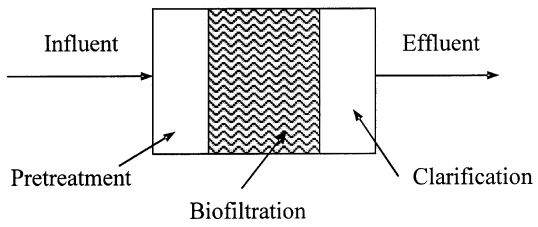

Fig. 7. Schematics of the package biofiltration system for the treatment of household wastewater.

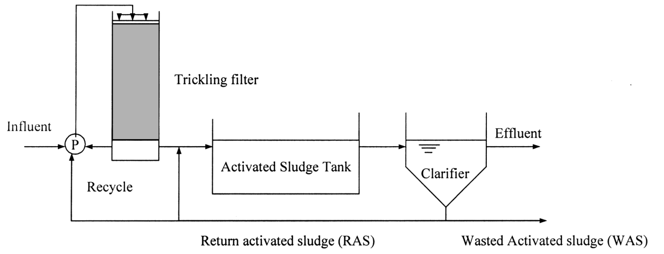

Fig. 8. Process diagram of the trickling biofiltration system for domestic wastewater treatment.

water.

Biofilter has successfully been used as a trickling filter for the domestic wastewater treatment. It can be used with and without other biological treatment processes depending on the characteristics of the influent, and the effluent quality requirement (Fig. 8). The rock, slag or plastic materials are used as the trickling biofilter media. The application options of trickling biofilter vary with the treatment objectives, the media type, and the nature of the other treatment units in the process train. It can be used for roughing, carbon oxidation, combined carbon oxidation and nitrification with different arrangements of two or more biofilters units. The advantages of using bio-trickling filter over the conventional activated sludge process are (i) less operational cost, (ii) less area requirement, (iii) well stabilized sludge (no sludge bulking or floating problem).

In advanced wastewater treatment, biofilter can be used along with conventional physico-chemical processes such as coagulation-flocculation, filtration and sedimentation (Fig. 9). The conventional filter and the biofilter units can be combined together depending on the suspended solid concentration. Since the main purpose of the biofilter is to remove the dissolved organics, the suspended particles are removed in conventional filter before subjecting the wastewater to the biofiltration system.

The biofilter has similarly been assessed by many researchers as an essential part of surface water treatment for potable to reduce the microbial growth in the distribution pipe lines, corrosion potential and the disinfection by-products [Bouwer and Crowe, 1988; Carlson and Amy, 1998]. Normally, GAC biofilter is recommended to use in the surface water treatment, as in GAC biofilter the organics are removed by both adsorption and biodegradation mechanisms (Fig. 10).

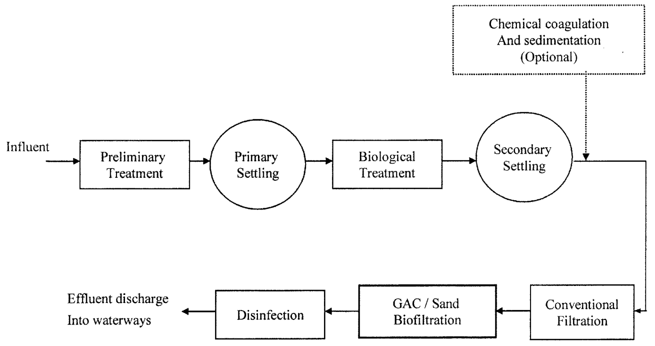

Fig. 9. Schematics of biofiltration system for advanced wastewater treatment.

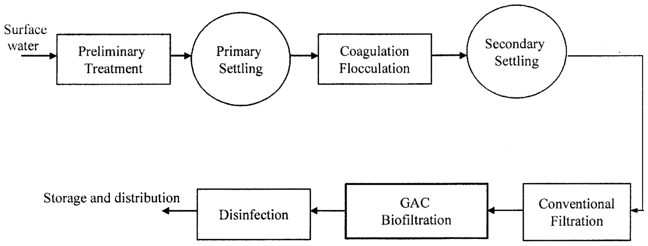

Fig. 10. Schematics of biofiltration system for surface water treatment.

PERFORMANCE OF BIOFILTER

In this section, the performance of biofilter in removing organics measured in different terms such as TOC and BOD_5, and some specific pollutants are discussed.

1. Surface Water Treatment

A study of GAC biofiltration system conducted at Neuilly-sur-Marne treatment plant, France by Servais et al. [1994] using three pilot filters with varying bed depth and filtration velocity, but similar empty bed contact time (EBCT) showed that organic removal efficiency of the GAC filter for a given EBCT is independent of filtration velocity in the range of 6-18 m/h. The organic removal efficiency of the filters is shown in Table 3. This study indicates that the removal of the biodegradable organic carbon increases with the biomass growth on the GAC surface, however the nonbiodegradable organic removal efficiency of the filter decreases.

An investigation of the GAC system at the Palo Alto Reclamation Facility, USA revealed that biofilter could have pseudo-steady state removal of 50% for the first year, 24% for the second year and 14% for the third year [Summers and Roberts, 1984]. Adsorption of organics and biological degradation of the organics adsorbed onto the activated carbon are two major mechanisms for the consistent removal of organics in the GAC biofiltration system.

The performance of biofilters at different plants in removing organics (TOC, DOC and AOC), ammonia, and nitrate are summarized in Tables 4, 5, and 6 respectively.

Table 3. Removal of biodegradable and nonbiodegradable dissolved organic carbon (BDOC and NBDOC) from the GAC pilot filters (adopted from Servais et al., 1994)

Filter	Influent (mgC/L)		Removal %	
	BDOC	NBDOC	BDOC	NBDOC
I	0.4	1.1	50	49
II	0.4	1.1	45	47
III	0.4	1.1	40	43
		After 7 months		
I	0.41	1.32	56	5
II	0.41	1.32	51	7
III	0.41	1.32	49	5

Filter I: GAC bed depth=1 m, filtration velocity=6 m/h, EBCT=10 min. Filter II: GAC bed depth=2 m, filtration velocity=12 m/h, EBCT=10 min. Filter III: GAC bed depth=3 m, filtration velocity=18 m/h, EBCT=10 min

Table 4. TOC removal efficiency of biofilters (adopted from Bouwer and Crowe, 1988)

Mode of operation	Location	Influent concentration	Reduction %
➢ Aerated biofilter (top layer GAC), full-scale	Annet sur Marne, France	3.2 mg TOC/L	38 *
➢ Fluidized bed, pilot-scale	Medmenham, UK	2.8 mg BOD_5/L	29
➢ Rapid sand filtration, full-scale	The Netherlands	23-500 μg AOC/L	3-84
➢ Biologically active GAC filter, full-scale	Mulheim, Germany	1.8-2.6 mg DOC/L	75*
➢ Biologically active GAC filter, full-scale (advanced wastewater treatment for ground water recharge)	Orange county, California, USA	25 mg DOC/L	20

*Preozonation employed.

Table 5. Ammonia removal efficiency of biofilters (adopted from Bouwer and Crowe, 1988)

Mode of operation	Location	Influent concentration mg NH_4-N/L	Reduction %
➢ Aerated biofilter, full-scale	Annet sur Marne, France	≤4	97
➢ Fluidized bed, pilot-scale	Medmenham, UK	≤2.0-2.5	≈100
➢ Rapid sand filtration, full-scale	Mulheim, Germany	1.0	≈100
➢ Biologically active GAC filter, full-scale	Mulheim, Germany	0.33	94
➢ Biologically active GAC filter, full-scale	Rouen la Chapelle, France	1.36	78

Table 6. Nitrate removal efficiency of biofilters (adopted from Bouwer and Crowe, 1988)

Mode of operation	Location	Influent concentration, mg NO_3-N/L	Reduction %
➢ Biofilter, full-scale	Eragny, France	37.9	84
➢ Biofilter, full-scale	Eragny, France	13.5	50
➢ Fluidized bed, full-scale	Stevenage, UK	15	63
➢ Fluidized bed, pilot-scale (26-45 mg methanol/L)	Bucklesham, UK	14	≈100

2. Low Strength Wastewater

An experimental study conducted by Chaudhary et al. [2001] at Environmental R&D Laboratory at University of Technology showed that GAC biofilter can be operated for a long time without regeneration of GAC. In this study, synthetic wastewater was prepared using three organic and seven inorganic substances [Organics: glucose, peptone, yeast extract; Inorganics: $MnSO_4$, $CaCl_2$, $NaHCO_3$, NaCl, $MgSO_4 \cdot 7H_2O$, KH_2PO_4, $(NH_4)_2 \cdot SO_4$], and the GAC bed was acclimatized with relatively lower filtration rate (1 m/h). The organic removal efficiency of the biofilter remained constant at 50-55% even after 77 days of continuous run (Fig. 11).

The daily backwash adopted to avoid the physical clogging of the biofilter did not seem to affect the organic removal efficiency of the filter. From the laboratory-scale filter study, Hozalski and Bouwer [1998] also found that biomass accumulation is not impaired by backwash with water. In their experiments, the organic removal efficiency of the biofilter was found to be unchanged after the backwash. Some of the biomass may naturally be lost during backwashing of the filter but the loss of biomass can create more sites for adsorption of organics and thus impairment is balanced. This can happen when the adsorption capacity of GAC is not fully exhausted.

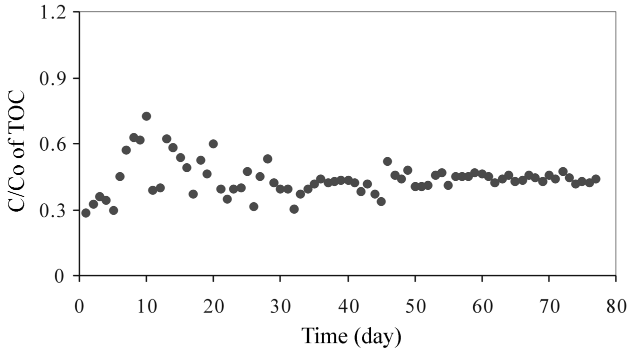

Fig. 11. TOC removal efficiency of the GAC biofilter (Filtration rate=1 m/h, average initial TOC concentration=3.5 mg/L) [Chaudhary et al., 2001].

The effects of both influent organic concentration and filtration rate on the organic removal efficiency of the biofilter were experimentally investigated [Chaudhary et al., 2001]. It was observed that with increased filtration rates, the effluent quality became inferior to that with lower filtration rate (at which the filter was acclimatized) but the organic removal pattern remained unchanged with time. It might be due to the fact that when the hydraulic loading rate of the biofilter was increased, the EBCT is decreased and the increased organic mass loading exceeded the ability of the biomass to assimilate the available biodegradable organic substances resulting in substandard effluent quality. It should be noted that the filter column was acclimatized with relatively low concentration of organics (TOC of 3.5 mg/L) and low filtration rate of 1 m/h for the gradual growth of biomass in the filter media.

The performance of the biofilter improved slightly when the influent TOC concentration was increased to 6.8 mg/L. The obvious reason for this improvement could be the increased biological activity of the microorganism. The first order steady-state model developed by Huck et al. [1994] also showed that the organic removal efficiency of the biofilter is approximately directly proportional to the influent organic concentration. However, when the influent concentration was increased from 6.8 mg/L to 11.2 mg/L, the removal efficiency of the filter was higher initially and then decreased with time. The experimental results thus indicates that the biomass profile is the most critical parameter in the design of a biofiltration system, and that the biofilter should be operated as close to steady-state conditions as possible to achieve optimum organic removal efficiency. The sudden increase in the flow rate and influent concentration can change the efficiency of the biofilter temporarily, but if the steady-state biomass condition is allowed to develop, the organic efficiency of the biofilter would be equivalent to that of the organic or hydraulic loading rate at which the filter is first acclimatized.

LeChevallier et al. [1992] and Prevost et al. [1992] have also observed decreases in the organic carbon removal with the decrease in EBCT. LeChevallier et al. [1992] found an increase in TOC removal from 29 to 51.2 percent when EBCT was increased from 5 to 20 min i.e. when the filtration velocity was decreased by four times. However, Carlson and Amy [1998] have reported from their pilot scale experimental studies that organic removal in a biofilter is limited either by biodegradable organic matter (BOM) formation or biomass concentration, not by filter operating parameters. They also found that optimum organic removal efficiency of the biofilter was at the loading rate to which the filter was acclimatized, and if the steady-state biomass conditions were allowed to develop, even at higher hydraulic loading rate, the removal efficiency of biofilter would increase to that found at the lower hydraulic loading rate (at which the filter was first acclimatized).

3. High Strength Wastewater

A full-scale study was conducted by Boon et al. [1997] employing six biofilter columns of different diameters (6-26 m) with blast-furnace slag and granite as filter media. The performance of the biofilters is summarized in Table 7. The BOD_5 and ammonia-N removal efficiency of the filters varied from 85%-97% and 55%-98% respectively.

CONCLUSION

1. Biofilter can effectively be used in an economical manner to produce high quality of effluent due to its consistent TOC removal efficiency, long operational life and simplicity in operation.

2. The biological activity led to a consistent effluent organic concentration over a long period of time. The daily backwash usually adopted to ease the filter bed seems to have no effect on the biomass growth rate, and hence the effluent quality. Its performance however can be affected by the filtration rate and the influent organic concentration, suggesting that the biofilter should be operated in the same conditions at which it is acclimatized for its optimum and consistent organic removal efficiency.

3. A correct choice of filtration rate and GAC medium depth with appropriate backwash can lead to a long-term operation with consistent and superior effluent quality.

4. The mathematical model should incorporate the biofilter parameters estimated for different operating conditions (such as acclimatization filtration rate and initial organic concentration) to verify the adaptability of the model in practice.

NOMENCLATURE

A : surface area normal to the filter media [m^2]
A_f : biofilm surface area [m^2]
a'_f : specific surface area of the pellet with biomass [m^2]
b_{tot} : total shear and decay loss [s^{-1}]
C : liquid phase organic concentration [mg/L]
C_0 : initial liquid phase organic concentration [mg/L]
D : molecular diffusion coefficient for the substrate in the bulk liquid phase [m^2/s]
D_{ax} : axial dispersion coefficient [m^2/s]
D_f : molecular diffusion coefficient within biofilm [m^2/s]
J : substrate flux into the biofilm [mg/m^2/s]
K_s : monod half-velocity coefficient [mg/L]
k : maximum specific rate of substrate utilization [mg of substrate/mg of biomass/s]
k_{max} : maximum rate of substrate utilization [mg/mg/s]
K_{dc} : decay coefficient [s^{-1}]
k_d : detachment rate coefficient [expression dependent units]
k'_d : detachment rate coefficient [expression dependent units]
k''_d : detachment rate coefficient [expression dependent units]
L : bed depth with biofilm [m]
L_d : diffusion layer thickness [m]
L_f : biofilm thickness [m]
L_o : initial bed depth [m]
n : number of pellet in contact
N : substrate uptake rate of the biofilm [mg/m^2/s]
r : radial distance measured from the center of the pellet [m]
R_p : radius of the pellet [m]

Table 7. Performance of biofilter for the treatment of high strength wastewater [Boon et al., 1997]

Biofilter diameter/size (m)	Flow (L/s)	Settled sewage					Final Effluent				
		Alkalinity (mg/L)	pH	Ammonia.N (mg/L)	BOD_5 (mg/L)	SS (mg/L)	Alkalinity (mg/L)	pH	Ammonia-N (mg/L)	BOD_5 (mg/L)	SS (mg/L)
16	3.24	142	6.6-8.2	19.1	108	84	9	5.8-6.2	<2.2	11	36
22	7.3	240	7.2-7.6	15.7	72	77	100	7.6-7.7	<2.0	7.2	17.5
26	27.2	300	7.4-7.8	22.5	136	118	120	7.5-7.7	<2.3	6.3	20
102×16.8	92.4	171	7.0-7.7	17.4	130	102	73	6.9-7.4	<2.5	14	30
6	0.92	165	6.9-7.3	23.5	146	126	79	6.7-7.2	14.6	24	45
6	0.44	331	7.0-8.0	44	265	146	166	7.0-8.0	19	32	53

r_d : rate for substrate accumulation due to diffusion [mg/m^3/s]
r_g : rate of biomass growth within the biofilm [mg/s]
r_u : rate of substrate utilization in the biofilm [mg/m^3/s]
S : substrate concentration in the bulk solution [mg/L]
S_b : substrate concentration in the biofilm [mg/L]
S_s : substrate concentration at the outer surface of the biofilm [mg/L]
t : time [s]
x : distance perpendicular to the pellet [m]
X_f : biomass density of biofilm [mg/L]
X_s : suspended biomass concentration [mg/L]
X_{s0} : initial suspended biomass concentration [mg/L]
Y : yield coefficient [mg/mg]
Z : distance normal to the biofilm surface [m]
z : distance along the biofilter length [m]

Greek Letters

β : filtration efficiency
ε : bed porosity
ε' : bed porosity with biofilm
ε_o : initial bed porosity
θ : empty bed contact time [s]
σ : biofilm shear loss coefficient [s^{-1}]
μ_g : specific biomass growth rate [s^{-1}]
μ_{gave} : average specific growth rate [s^{-1}]
v : fluid velocity [m/s]
τ : fluid shear stress [Nm^{-2}]

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