MODELING OF BIOFILTRATION FOR REMOVAL OF HEAVY METALS FROM WASTEWATER

A DISSERTATION

Submitted in partial fulfilment of the
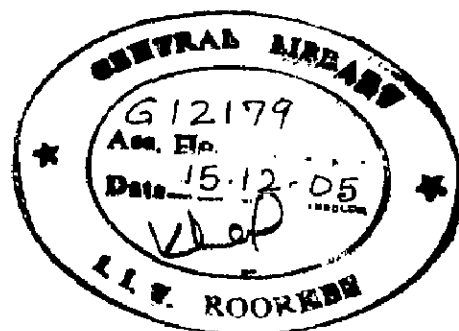*requirements for the award of the degree*
of
MASTER OF TECHNOLOGY
in
CHEMICAL ENGINEERING
(With Specialization in Computer Aided Process Plant Design)

By

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DEPARTMENT OF CHEMICAL ENGINEERING
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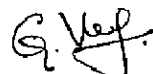ROORKEE-247 667 (INDIA)
JUNE, 2005

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the project entitled **"MODELING OF BIOFILTRATION FOR REMOVAL OF HEAVY METALS FROM WASTEWATER"**, in partial fulfillment of the requirement for the award of the degree of **Master of Technology** in **Chemical Engineering** with specialization in **"Computer Aided Process Plant Design"**, submitted in the **Department of Chemical Engineering, Indian Institute of Technology Roorkee, Roorkee** is an authentic record of my own work carried out during the period from July 2004 to June 2005, under the guidance of **Dr. C.B. Majumder**, Assistant Professor, Department of Chemical Engineering, Indian Institute of Technology Roorkee.

The matter embodied in this project work has not been submitted for the award of any other degree.

Date: 30ᵗʰ June 2005

Place: IIT, Roorkee

(GIDDALURU VEERENDRA)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr. C.B. Majumder

Assistant professor

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ABSTRACT

Biofilter is fast emerging as an important wastewater treatment facility. This is because it has got many advantages over the conventional treatment facilities concerning design as well as operating conditions, like Design without complex technical devices, compactness, no noise and no odor emissions. Biofilter consists of a packed bed of support media on which the microorganism grows and forms the biofilm which in turns degrades or accumulates the impurities. On reaching the saturation capacity of microorganisms, we have to backwash the biofilter. In this case biofilter is used to treat heavy metals such as cobalt, lead, and manganese. In order to study the performance of a biofilter it is essential to understand the complex process occurring in biofilter. With an apropos to the above, the mathematical model appears to have an unmatched concerns for analysis and simulation of process. Thus it is desirable to develop a mathematical model for removing heavy metals from wastewater using biofilter.

In the present dissertation work, an unsteady state model for biofilter has been developed which incorporates partial differential equations along with initial conditions as well as Danckwerts boundary conditions. The model equations are solved by using MATLAB PDE (Partial Differential Equations) solvers.

The laboratory scale operating data are available in literature, were selected for testing the model predictions and to ascertain the correctness of the proposed model. The concentration profiles of manganese, cobalt, and lead in biofilter with time have been computed and compared with those reputed in the literature. The results are found to be in good agreement. The concentration profiles along the length have also been computed.

The simulation calculations are carried out for treatment of three metals cobalt, lead, manganese under operating conditions collected from literature. The concentration profiles of all the three metals along the length of the biofilter with time have been studied. Simulations have been performed to know the best flow rate using bioaccumulation rate (metal accumulated in $\mu g/l.h$) as the criteria. In the view of above simulation results it is concluded that proposed model may be used for the analysis of biofilter and optimization of its operation.

ACKNOWLEDGEMENTS

Place: Roorkee

Giddaluru Veerendra

Date:30thJune, 2005.

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NOMENCLATURE

C_i	Heavy metal concentration	M/L^3
C^*	Equilibrium concentration of heavy metal in biofilm	M/L^3
D	Dispersion coefficient	L^2/T
d_m	Diameter of the biofilter	L
d_c	Packing material size	L
K	Adsorption constant	dimensionless
L	Length of the biofilter	L
q	Amount of heavy metal adsorbed	M/L^3
S	Cross sectional area of the biofilter	L^2
v	Velocity	L/T
z	Length coordinate of the biofilter	L

INTRODUCTION

The usage of metals goes back to prehistoric days when metals like copper, silver and other precious metals were used as raw materials. Since then they have been used extensively in industries, agriculture, food processing, domestic etc. With the rising population and rapid industrialization of the country the usage of metals has increased several fold. Consequently effluents discharging from industries and other sectors contain high concentration of objectionable metals. Over the past two decades, the term "heavy metals" has been used increasingly in various publications and in legislation related to chemical hazards and the safe use of chemicals. It is often used as a group name for metals and semimetals (metalloids) that have been associated with contamination and potential toxicity or ecotoxicity [John H. Duffus et al, 2001]. At the same time, legal regulations often specify a list of heavy metals to which they apply. Such lists may differ from one set of regulations to the other, or the term may be used without specifying which heavy metals are covered. It is, therefore, necessary to review the usage that has developed for the term.

1.1. DESCRIPTION OF THE TERM "HEAVY METALS"

1.1.1 Definitions in terms of density (specific gravity)

- Metals fall naturally into two groups—the light metals with densities below 4, and the heavy metals with densities above 7.
- Metal having a specific gravity greater than 4.
- Metal of high specific gravity, especially a metal having a specific gravity of 5.0 or greater.
- Metal with a density greater than 5 g/cm^3.
- Metal with a density greater than 6 g/cm^3.

1.1.2 Definitions in terms of atomic weight (mass)

- Metal with a high atomic weight.

- Metal of atomic weight greater than sodium.

- Metal of atomic weight greater than sodium (atomic weight: 23) that forms soaps on reaction with fatty acids.

- Metallic element with high atomic weight (e.g., mercury, chromium, cadmium, arsenic, and lead); can damage living things at low concentrations and tend to accumulate in the food chain.

- Metallic element with an atomic weight greater than 40 (starting with scandium; atomic number 21) excluded are alkaline earth metals, alkali metals, lanthanides, and actinides.

- Heavy metals is a collective term for metals of high atomic mass, particularly those transition metals that are toxic and cannot be processed by living organisms, such as lead, mercury, and cadmium.

1.1.3 Definitions in terms of atomic number

1.1.3.1 in biology:

- In electron microscopy, metal of high atomic number used to introduce electron density into a biological specimen by staining, negative staining, or shadowing.

- In plant nutrition, a metal of moderate to high atomic number, e.g., Cu, Zn, Ni, or Pb, present in soils owing to an outcrop or mine spoil, preventing growth except for a few tolerant species and ecotypes.

1.1.3.2 in chemistry:

- The rectangular block of elements in the Periodic Table flanked by titanium, hafnium, arsenic, and bismuth at its corners but including also selenium and tellurium. The specific gravities range from 4.5 to 22.5.

- Any metal with an atomic number beyond that of calcium.

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- Any element with an atomic number greater than 20.
- Metal with an atomic number between 21 (scandium) and 92 (uranium).

1.1.4 Definitions based on other chemical properties

- Heavy metals are the name of a range of very dense alloys used for radiation screening or balancing purposes. Densities range from 14.5 for 76% W, 20% Cu, 4% Ni to 16.6 for 90% W, 7% Ni, 3% Cu.

- Intermetallic compound of iron and tin ($FeSn_2$) formed in tinning pots that have become badly contaminated with iron. The compound tends to settle to the bottom of the pot as solid crystals and can be removed with a perforated ladle.

- Lead, zinc, and alkaline earth metals that react with fatty acids to form soaps. "Heavy metal soaps" are used in lubricating greases, paint dryers, and fungicides.

- Any of the metals that react readily with dithizone ($C_6 H_5 N$), e.g., zinc, copper, lead, etc.

1.1.5 Definitions without a clear basis other than toxicity

- Element commonly used in industry and generically toxic to animals and to aerobic and anaerobic processes, but not every one is dense or entirely metallic; includes As, Cd, Cr, Cu, Pb, Hg, Ni, Se, and Zn.

- Outdated generic term referring to lead, cadmium, mercury, and some other elements that generally are relatively toxic in nature; recently, the term "toxic elements" has been used. The term also sometimes refers to compounds containing these elements.

1.1.6 Definitions preceding 1936

- Guns or shot of large size.
- Great ability.

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1.2   HEAVY METALS:

Scientists have identified fourteen metals and metalloids, each with a high molecular weight, which they include in this list of heavy metals [Jennifer et al, 2002]:

Antimony (Sb), Arsenic (As), Bismuth (Bi), Cadmium (Cd), Chromium (Cr), Copper (Cu), Indium (In), Lead (Pb), Mercury (Hg), Selenium (Se), Manganese(Mn), Thallium (Tl), Tin (Sn), Zinc (Zn).

1.3   SOURCES:

There are two categories of sources of heavy metals emissions into the environment: natural and anthropogenic.

The natural sources of heavy metal emission are the erosion and alteration of rocks. This makes heavy metals available to plants and animals in soil and water. The concentration of heavy metals in a rock depends on the type of rock. Rocks that contain metallic ores have much higher concentrations than rocks that do not. They can easily be dissolved by rain or surface waters, because their metal ore deposits are made up of oxides and sulphurous minerals, which react easily with water. Because of this, they can contaminate underground and surface waters.

Anthropogenic sources are not natural. Instead, they are sources of pollution from industry and other processes.

Depending on the types of the emission there are two types of sources. They are diffuse sources and stationary sources.

Diffuse sources are most common in urban areas. The concentration of heavy metals in street dust is very high due to the heavy traffic in highly populated, urban areas. The main heavy metals in urban street dust are lead, from automobile emissions, and cadmium, from the rubber used to make tires.

Most of the stationary sources of heavy metal pollutants are industrial. Industries, such as mining, metal processing, and those that burn fossil fuels let out heavy metals into wastewater or the air. The heavy metals are then transported by wind or runoff water, and contaminate air and water sources miles from the industrial site. Heavy metals in consumer goods and industrial processes also enter the environment when we burn or

dump wastes. Because these heavy metals are elements, they do not degrade. They can only change their form.

1.4 IMPACT MECHANISM OF HEAVY METALS ON THE ENVIRONMENT:
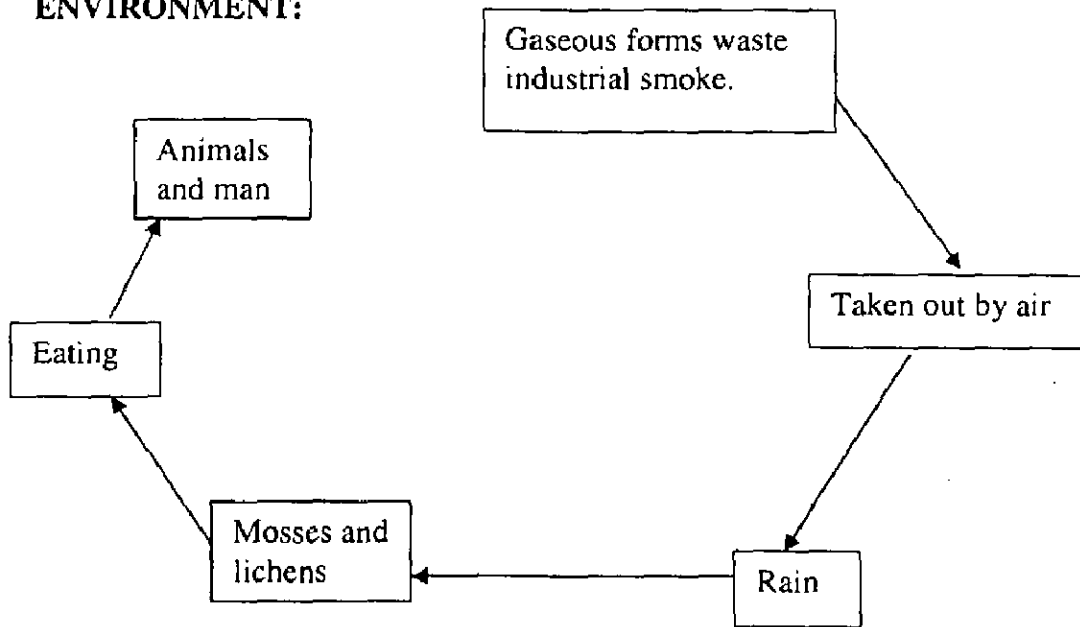
Figure1.1. Urban area

Figure1.2. Rural area

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┌─────────────────┐
│ Waste stream of │
│ industries      │
└─────────────────┘
                      ┌──────┐
┌─────────────┐       │ Soil │
│ Animals     │       └──────┘
│ and man     │
└─────────────┘
        ┌────────────────┐
        │ Growing plants │
        └────────────────┘
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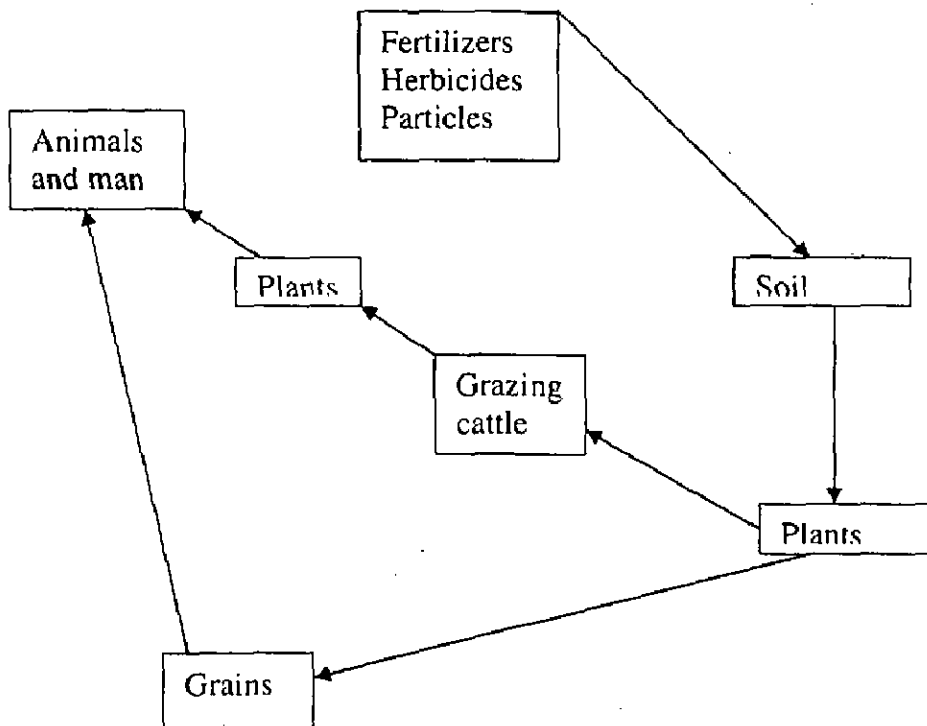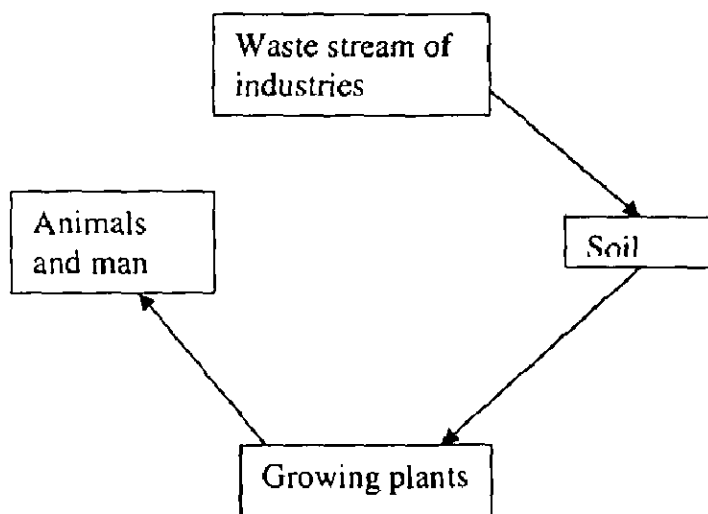
Figure1.3. Industrial area

The absorption rate of the material and its effect on the biochemical process also determine the toxicity of heavy metals. Metals that can enter the biological membranes that protect the brain or blood cells are the most dangerous. For example, liquid mercury is not very toxic, but vapors of mercury are very dangerous because they can be inhaled and enter the bloodstream.

Heavy metals also can bond easily with the sulfhydril (sulfur-hydrogen-related) group of enzymes. These are the enzymes that control the speed of metabolic reactions in living things. This is another reason why heavy metals are harmful to plants, animals, and humans.

A third reason why heavy metals are toxic is because of bioaccumulation. Heavy metals tend to accumulate in living things. This means that as you move up the food chain the concentration of heavy metals increases.

Various chronic effects have been detected on human by heavy metals. The effects of heavy metal toxicity studies confirm that heavy metals can directly influence behavior by impairing mental and neurological function, influencing neurotransmitter production and utilization and altering numerous metabolic body processes. Systems in which toxic metal elements can induce impairment and dysfunction include the blood and cardiovascular, detoxification pathways (liver, kidneys, skin), endocrine (hormonal),

energy production pathways, enzymatic, gastrointestinal, immune, nervous (central and peripheral), reproductive and urinary. Breathing heavy metal particles, even at levels well below those considered non-toxic, can have serious health effects. Virtually all aspects of animal and human immune system function are compromised by the inhalation of heavy metal particulates. In addition, toxic metals can increase allergic reactions, cause genetic mutation, compete with "good" trace metals for biochemical bond sites, and act as antibiotics, killing both harmful and beneficial bacteria.

Much of the damage produced by toxic metals stems from the proliferation of oxidative free radicals they cause. A free radical is an energetically unbalanced molecule, composed of an impaired electron that "steals" an electron from another molecule to restore its balance. Free radicals results naturally when cell molecules react with oxygen (oxidation) but, with heavy toxic lead or existing antioxidant deficiencies, uncontrolled free radical production occurs. Unchecked, free radicals can cause tissue damage throughout the body; free radical damage underlies all degenerative diseases. Antioxidants such as vitamins A, C, and E curtail free radical activity.

Heavy metals can also increase the acidity of the blood. The body draws calcium from bones to help restore the proper blood pH. Further, toxic metals set up conditions that lead to inflammation in arteries and tissues, causing more calcium to be drawn to the area as a buffer. The calcium coats the inflamed areas in the blood vessels like a bandage, patching up one problem but creating another, namely the hardening of the artery walls and progressive blockage arteries. Without replenishment of calcium, the constant removal of this important mineral from the bones will result in osteoporosis (loss of bone density to brittle bones).

Current studies indicate that even minute levels of toxic elements have negative health consequences; however, these vary from person to person. Nutritional status, metabolic rate, the integrity of detoxification pathways (ability to detoxify toxic substances), and the mode and degree of heavy metal exposure all affect how an individual responds.

It is clear from the above information that accumulation of heavy metals in the environment is extremely dangerous to mankind and other living things. In an effort to curtail the accumulation of heavy metals in environment, Central pollution control board,

India has set standards for effluents from various industries [Sudha Sagar, R., et al 2004].

Table1.1. Pesticide industry

Parameter	Toxicity limit mg/l
Cu	1.0
Mn	1.0
Zn	1.0
Hg	0.01
Sn	0.1
Any other	Shall not exceed 5 times the drinking water standards (BIS) individually

Table1.2. Pharmaceutical industry

Parameter	Toxicity limit mg/l
Mercury	0.01
Arsenic	0.2
Chromium (hexavalent)	0.1
Lead	0.1
Cyanide	0.1
Phenolics (C_6H_5OH)	1.0
Sulfide (as S)	2.0

1.5. CONVENTIONAL WASTEWATER TREATMENT TECHNOLOGIES:

Removal of heavy metals from industrial wastewater is of primary importance. This is because contamination of wastewater by heavy metals is a very serious environmental problem. The wastewater treatment systems range from simple

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clarification in a settling pond to a complex system of advanced technologies requiring sophisticated equipments and skilled operators. The technologies can be divided into three broad categories: physical, chemical and biological. There are a multitude of technologies for each of these categories. Most of treatment systems combine two or all three categories to provide the most effective treatment.

1.5.1 Physical and chemical treatment:

The commonly used procedures for removing metal ions from aqueous streams include chemical precipitation, lime coagulation, ion exchange, reverse osmosis and solvent extraction. The process description of each method is presented below.

1.5.1.1. Reverse Osmosis: It is a process in which heavy metals are separated by a semi-permeable membrane at a pressure greater than osmotic pressure caused by the dissolved solids in wastewater. The disadvantage of this method is that it is expensive.

1.5.1.2. Electrodialysis: In this process, the ionic components (heavy metals) are separated through the use of semi-permeable ion selective membranes. Application of an electrical potential between the two electrodes causes a migration of cations and anions towards respective electrodes. Because of the alternate spacing of cation and anion permeable membranes, cells of concentrated and dilute salts are formed. The disadvantage is the formation of metal hydroxides, which clog the membrane.

1.5.1.3. Ultrafiltration: They are pressure driven membrane operations that use porous membranes for the removal of heavy metals. The main disadvantage of this process is the generation of sludge.

1.5.1.4. Ion exchange: In this process, metal ions from dilute solutions are exchanged with ions held by electrostatic forces on the exchange resin. The disadvantages include: high cost and partial removal of certain ions.

1.5.1.5. Chemical Precipitation: Precipitation of metals is achieved by the addition of coagulants such as alum, lime, iron salts and other organic polymers. The large amount of sludge containing toxic compounds produced during the process is the main disadvantage.

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1.5.1.6. Coagulation: Coagulation sedimentation combined chemical precipitation (coagulation/ flocculation treatment) and gravity sedimentation is employed for removing lightweight suspended solids and colloidal solids from water. Coagulation-precipitation is additionally applicable to remove heavy metals in wastewater.

1.5.2 Biological Treatment:

Biological wastewater treatment is generic term applied to processes that use microorganisms to decompose organic matters in wastewater and is roughly classified into two categories: aerobic treatment and anaerobic treatment.

1.5.2.1. Aerobic Treatment: Aerobic treatment is a method for decomposing organic matter into water, carbon dioxide and simple inorganic substances by using aerobic microorganisms. Additionally, the microorganisms may be used for deodorization, denitrification and dephosphorization.

1.5.2.2 Anaerobic Treatment: Anaerobic treatment is a method for decomposing organic matter by using anaerobic microorganisms in closed system under the absence of air. Organic matter in wastewater is generally degraded and treated through two steps of biochemical reaction. In the first acid fermentation step, the organic matter is degraded into low-grade fatty acid. In the next step for methane fermentation, the low-grade fatty acid is degraded and methane gas is produced in the process.

Among the above-mentioned conventional and advanced techniques for removing heavy metal from contaminated water, the biological processes are gradually getting high momentum due to the following reasons:

- No use of chemicals in the process
- Low operating cost
- Eco-friendly and cost effective nature
- Obtained removal efficiency above 80%, can be effective for separation in the lower concentration level.

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1.6. VARIOUS BIOPROCESSES FOR METAL REMOVAL FROM CONTAMINATED WATER

- Aerobic digestion
- Activated sludge process
- Anaerobic digestion
- Bio-filters

Among the mentioned biological processes biofilter is one of the most important separation processes that can be employed to remove pollutants from air, water and wastewater.

1.7 ORGANISATION OF THESIS

Chapter I includes the definition of heavy metals, their effects on living things, brief description of available wastewater treatment technologies. Chapter II discusses about types of biofilters, their design and modeling. Chapter III gives a brief literature review. Chapter IV includes the model development. Chapter V gives results and discussion of results obtained from this model. Chapter VI gives the concluding remarks and future recommendations.

BIOFILTERS

A biofilter is usually filled with particles of a carrier material – the "support" – where the microbial film is attached. If the particles are porous, the film forms not only on the surface but also within their pores. A limiting case of a very simple biofilter is a duct where the biomass develops on the walls: such a situation actually occurs in sewers, where the adhered biomass may act as an additional wastewater treatment biofilter, although in some cases it also contributes to the deterioration of the wall material. Another example is the case of biofilms formed on rocks in contact with mountain streams that help to purify these waters.

One of the oldest examples of artificial biofiters was promoted by Fredirich II of Prussia who had lime walls built and put in contact with flowing liquid manure. The presence of ammonium compounds and bacteria in the liquid waste resulted in the development of nitrifying biofilms inside and on the lime stone, which converted ammonium to nitrate and contributed to the formation of calcium nitrate by reaction with calcium of the lime walls. The purpose was to obtain potassium nitrate for gunpowder production

In industrial biofilters, the fluid flows in contact with the biofilm particles promoting the exchange of nutrients and metabolic products between the fixed biomass and the surrounding fluid. There is also exchange of mechanical energy between the two media: on one hand, the liquid exerts hydrodynamic forces on the biofilm enhancing both the detachment of biomass and the compactness of biofilms (these effects are particularly important in turbulent flow systems); on the other hand, the roughness and viscoelasticity of the microbial film increase the pressure drop of the fluid along the length of the biofilter.

The tendency for cells to attach to supports in a biofilter is determined not only by the physical-chemical properties of the surfaces, but also by the relative

values of the specific microbial growth rate and the hydraulic residence time. When the residence time of the fluid in the biofilter is small compared to the replication time of the cells, attachment becomes particularly relevant in avoiding the washout of the micro-organisms. The cells will then tend to adhere to the supports if the physical-chemical surface interactions are favorable.

Invariably, suspended biomass may also grow in biofilters, although, if needed. This phenomenon can be minimized in many cases through proper design and operating procedures. Anyhow, since biofilms are dynamic structures, biologically speaking, a part of the biomass that is continuously building up on the supports has to be periodically purged from the system. This can be achieved through proper washing cycles (often, back washing) in conjunction with external solid liquid separation or through sedimentation of the detached biomass on the bottom zones of the biofilter.

2.1. TYPES OF BIOFILTERS:

In terms of particle-fluid dynamics biofilters are often classified as fixed bed or expanded bed biofilers. The latter include classical fluidized beds where particles move up and down in the bed while the expanded bed as a whole is kept within a well-defined zone of the biofilter. The so called moving beds where the whole expanded bed circulates throughout the equipment together with the fluid, such as in air-lift reactor, moving bed or circulating bed reactors. In those reactors the bed is usually expanded by the liquid, sometimes containing gas bubbles, flowing upwards with a sufficiently high velocity to lift the bed. Recently, biofilm support particles made of low density material, which tend to float in water, have been used in reactors where the bed is expanded by circulating the liquid downwards; this is the so called inverse fluidized bed.

Fixed beds can be divided into: 1) submerged beds, where the biofilm particles are completely immersed in the liquid (up flow or down flow circulation); 2) Trickling filters, where the liquid flows downwards split in small isolated streams as it percolates through the biofilm bed, while the gas usually flows upwards, and 3) rotating disk reactors, where the biofilm develops on the

surface of vertical disks that rotate within the liquid. In aerobic processes, the lower part of each rotating disk is periodically submerged in the liquid and the upper zone is in contact with air; in anaerobic or anoxic processes, the disk is (almost) completely submerged at any time, in order to avoid contact of the biofilm with the air.

Table2.1: Design parameters of several innovative fixed bed processes developed in industrial scale

Process (Flow direction)	Medium	Volumetric loads (kg m^{-3}d^{-1})	Hydraulic loads (m^3 m^{-2} h^{-1})
Biofor (UF)	Expanded clay Biolite, 2-5mm	5 -18 (COD), 0.5 -1.5(N-NH$_4$), 5 (N-NO$_3$)	Up to 35
Biocarbone (DF)	Expanded clay Biodamine, 2-5mm	5-10 (COD)	Up to 10
B2A (UF)	Multi-media, 3 layers, 1 -40 mm.	25 (COD), 0.7 (N-NH$_4$)	
Nitrazur (UF)	Biolite L 1.7 -2.7 mm	3.1 -9.5 (NO$_3$)	8.2
Biodenit (DF)	Biodagene, 3 -6mm	3-5 (NO$_3$)	
Sulfur/limest one (UF)	2 -6mm sulfur and limestone		9.75
Dynasand	Sand 1.2-2mm	2.7 (N-NO$_3$),	5.4 - 24.5

(UF)		1.6 (N-NH$_4$)	
Biostyr (UF)	Expanded Poly Styrene 1-2mm	5 (COD), 0.5 -1.5(N-NH$_4$)	10
Denitropur (UF)	Plastic elements Mellapak	0.5 (N-NO$_3$)	
Denipor (UF/DF)	Expanded Poly Styrene 2-3mm	0.7 -1 (N-NO$_3$)	
Biobead (UF)	Poly Ethylene or Poly Propylene, 2-5mm	0.35 (N-NH$_4$)	

2.1.1. Submerged Biofilters

Aerobic submerged fixed –film processes consist of three phases: a packing, biofilm, and liquid. The BOD and/or NH$_4$-N removed from the liquid flowing past the biofilm is oxidized. Oxygen is supplied by diffused aeration into the packing or by being predissolved into the influent wastewater. No clarification is used with aerobic submerged attached growth processes, and excess solids from biomass growth and influent suspended solids are trapped in the system and must be periodically removed. Most designs require a backwashing system much like that used in a water filtration plant to flush out accumulated solids, usually on a daily basis.

The distinguishing feature of a submerged filter is that the media is always submerged completely below the water surface. There are two common operational modes for submerged filters. When the water flows from the top of the filter downward and out the bottom filter it is called a down flow filter. When water flow is from bottom to top it is referred to as an up flow filter. Occasionally submerged filters are operated such that water flows horizontally through the filter. This mode is called a cross flow filter. The type and size of packing is a major factor that affects the performance and

operating characteristics of submerged biofilters. Designs differ by their packing configuration and inlet and outlet flow distribution and collection.

The major advantages of submerged biofilters are their relatively small space requirement, the ability to effectively treat dilute wastewaters, no sludge settling issues as in activated-sludge process, and aesthetics. Also for many processes solids filtration occurs to produce a high-quality effluent. Such fixed-film systems have equivalent hydraulic retention times of less than 1 to 1.5 h, based on their empty tank volumes. Their disadvantages include a more complex system in terms of instrumentation and controls, limitations of economies of scale for application to larger facilities, and generally a higher capital cost than activated-sludge treatment.

2.1.1.1. Biocarbone Process:
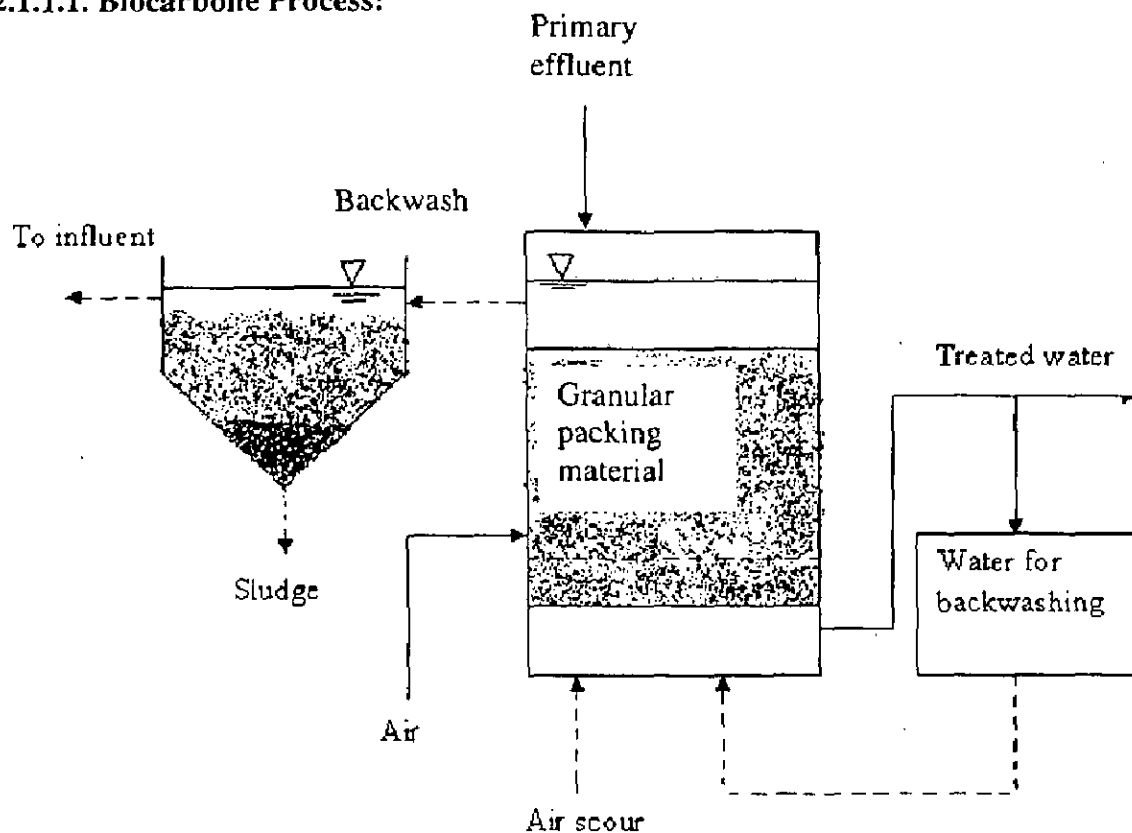
Figure2.1. Schematic of Biocarbone downflow biological process.

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The Biocarbone process is a typical example of a down flow submerged biofilter process. Over 100 facilities have been constructed worldwide since the development of the process in France in the early 1980s. The process has also been termed the biological aerated filter. Although activated carbon packing was used in the original design, a 3-5mm fired clay material is used in current designs. Plant installations range in size from 2000 to 80000 m³/d. A Schematic of the Biocarbone process is shown on figure. The system is designed much like a water filter with the addition of an air header about 300 mm above the under drain nozzles to sparge air through the packing. The air header is uniformly arranged across the bed to assure that oxygen is provided throughout the entire bed of packing. The actual oxygen transfer efficiency is in the range of 5 to 6 percent, which is comparable to fine bubble diffused aeration performance for that depth.

Backwashing is normally done once per day or when the headloss increases to about 1.8 m. The design must consider both organic loading and hydraulic application rate. Hydraulic application rates in the range of 2.4 to 4.8 m³/m².h are recommended to prevent excessive head loss. The Biocarbone process has been used in aerobic applications for BOD removal only, combined BOD removal and nitrification, and tertiary nitrification. Typical design loadings for Biocarbone applications are presented in table.

Table2.2: Typical design loadings for Biocarbone aerobic submerged attached growth process

Application	Unit	Loading range
BOD removal	Kg BOD/m³.d	3.5-4.5
BOD removal and nitrification	Kg BOD/m³.d	2.0-2.75
Tertiary nitrification	Kg N/m³.d	1.2-1.5

2.1.1.2. Biofor Process:

The Biofor up flow biofilter has a typical bed depth of 3 m but designs in the range of 2 -4 m bed depth have been used. The packing, termed Biolite, is an expanded clay material with a density greater than 1.0 and 2 -4 mm size range. Inlet nozzles distribute the influent wastewater up through the bed, and an air header provides process air across the bed area. Backwashing is typically done once per day with a water flush rate of 10 to 30 m/h to expand the bed. Fine screening of the wastewater is needed to protect the inlet nozzles. The Biofor process has been applied for BOD removal and nitrification, tertiary nitrification, and denitrification. Recommended operating limits for the Biofor process are show in table.
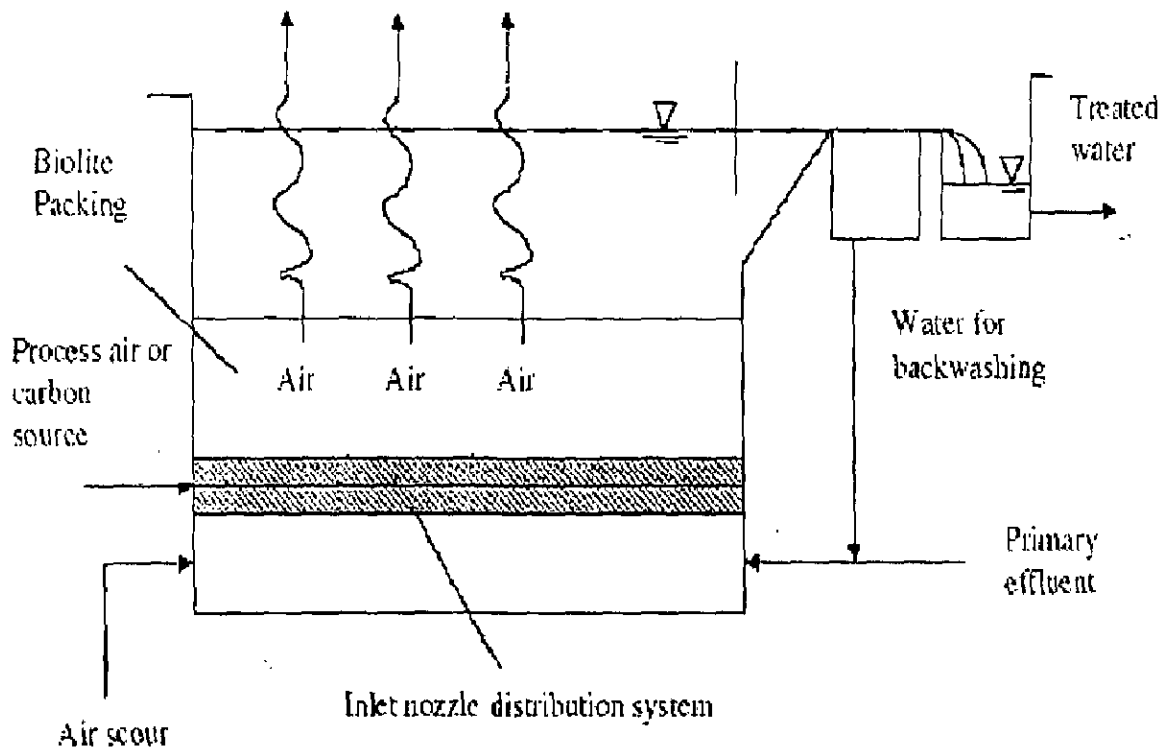
Figure 2.2 Schematic of Biofor upflow biological process

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Table2.3: Recommended operating limits for the Biofor process

Item	Unit	COD removal	Tertiary nitrificatio n
Installed packing porosity	%		~40
Loading	Kg COD/m^3.d	10-12	
	Kg N/m^3.d		1.5 -1.8
Hydraulic application	m^3/m^2.h	5.0 -6.0	10 -12

2.1.1.3. Biostyr Process:

Process and
backwash air

Feed channel

Treated water outlet and
backwash water storage

Screen cover

Process air

aerobic zone

Polystyrene
packing

anoxic zone

Primary
effluent

Air for scouring

Backwash water
extraction

Distribution and
collection channel
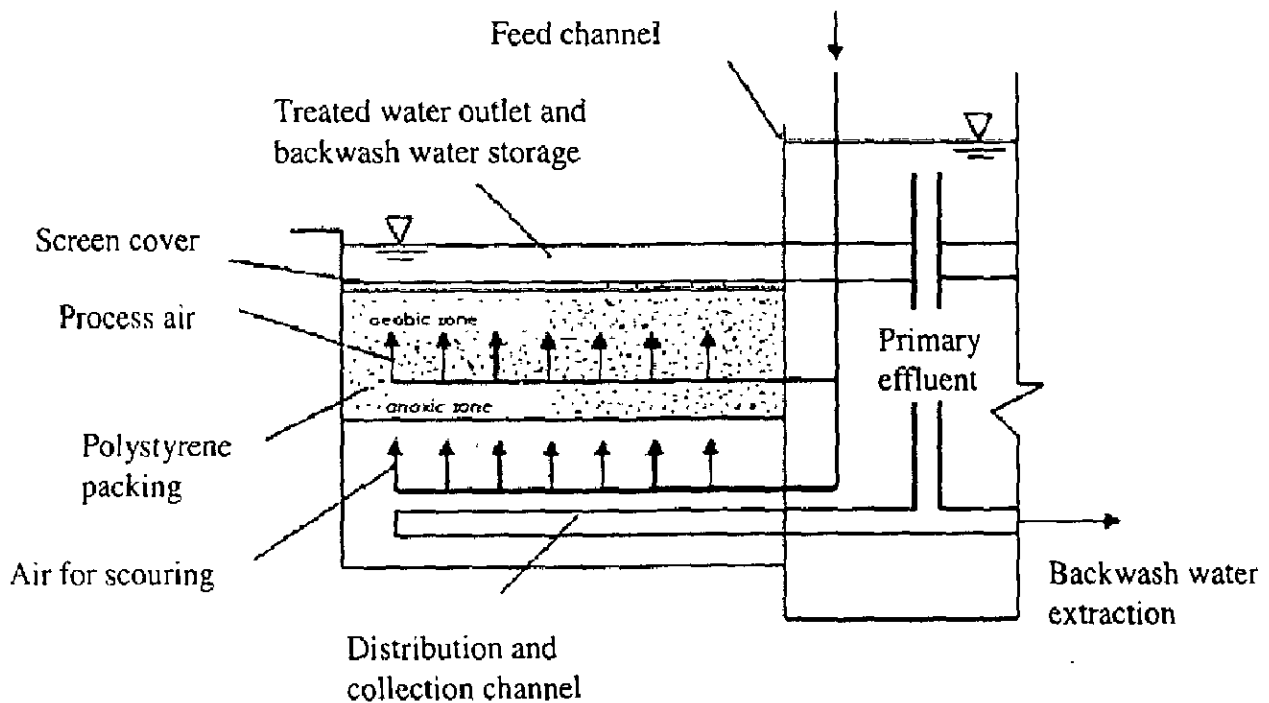
Figure 2.3. Schematic of Biostyr upflow biological process

The Biostyr process is an upflow process, developed in Denmark, and uses 2 – 4 mm (specific area about 1000 m^2/m^3) polystyrene beads that have a specific density less than water. The installed packing porosity is about 40 percent, providing an effective area of about 400 m^2/m^3 for biofilm growth. Packing depths range from 1.5 to 3 m. A schematic of the Biostyr process is shown in fig2.3. The bed can be operated entirely aerobic by providing air at the bottom or as an anoxic/aerobic bed by providing air at an intermediate level. Nitrified effluent is recycled for the anoxic/aerobic operation. The floating packing is retained by nozzle plates and is compressed as the wastewater flows upward to provide filtration. Backwash water is stored above the treatment bed. During the backwash cycle treated water flows down through the packing at a very high rate, which results in a downward expansion of the originally compressed packing. The solids retained in the lower portion of the reactor tank. The normal backwash procedure consists of repeated rinse (water flushing) and air scouring steps. Typically four water phases and three air phases are used.

The Biostyr process has been used for BOD removal only, combined BOD removal and nitrification, tertiary nitrification, and postdenitrification. Typical loadings possible for the various types of treatment with the Biostyr process are presented in table.

Table2.4: Typical design loadings for the Biostyr process

Application	Unit	Value
BOD only	kg COD/m^3.d	8 -10
BOD removal and Nitrification	kg COD/m^3.d	4 -5
Tertiary Nitrification	kg N/m^3.d	1.0 - 1.7

2.1.2. Trickling Filters

Trickling filters have been used to provide biological wastewater treatment of municipal and industrial wastewaters for nearly 100 years. As noted above, the trickling filter is a nonsubmerged fixed-film biological reactor using rock or plastic packing over which wastewater is distributed continuously. Treatment occurs as the liquid flows over the attached biofilm. The depth of the rock packing ranges from 0.9 to 2.5 m(3 to 8ft) and averages 1.8 m (6 ft). Trickling filters that use plastic packing have been built in round, square, and other shapes with depths varying from 4 to 12m (14 to 40 ft). Influent wastewater is normally applied at the top of the packing through distributor arms that extend across the trickling filter inner diameter and have variable openings to provide a uniform application rate per unit area.

Facultative bacteria are the predominating organisms in trickling filters, and decompose the organic material in the wastewater along with aerobic and anaerobic bacteria. Achromobacter, Flavobacterium, Pseudomonals, and Alcaligeses are among the bacterial species commonly associated with the trickling filter. The fungi present are also responsible for waste stabilization, but their role is usually important only under low-pH conditions or with certain industrial wastes. At times, fungi growth can be so rapid that the filter clogs and ventilation becomes restricted.

2.1.3. Biodisks

Rotating biological contactors (RBCs) were first installed in West Germany in 1960 and later introduced in the United States. An RBC consists of a series of closely spaced circular disks of polystyrene or polyvinyl chloride that are submerged in wastewater and rotated through it. Plate spacing along the length of the shaft is minimized while maintaining enough space for wastewater to circulate between plates after a bacterial film has been established on both sides of each plate. The shaft passes through the center of each plate and is mounted in bearings attached to each end of the wastewater container. The mounting is located such that the plates are submerged in the

wastewater to approximately one-half of their diameter. The shaft and plates attached to it are rotated by a power source, usually an electric motor. Flow through a biodisk is usually parallel to the shaft. The cylindrical plastic disks will be having standard unit sizes of approximately 3.5 m (12ft) in diameter and 7.5 m (25 ft) in length. The surface are of the disks for a standard unit is about 9300 m^2, and a unit with a higher density of disks is also available with approximately 13,900 m^2 of surface area. The RBC unit is partially submerged (typically 40 percent) in a tank containing the wastewater, and the disks rotate slowly at about 1.0 to 1.6 revolutions per minute. Mechanical drives are normally used to rotate the units, but air-driven units have also been installed. In the air-driven units, an array of cups is fixed to the periphery of the disks and diffused aeration is used to direct air to the cups to cause rotation. As the RBC disks rotate out of the wastewater, aeration is accomplished by exposure to the atmosphere. Wastewater flows down through the disks, and solids sloughing occur. Similar to a trickling filter, RBC systems require pretreatment of primary clarification or fine screens and secondary clarification for liquid/solids separation.
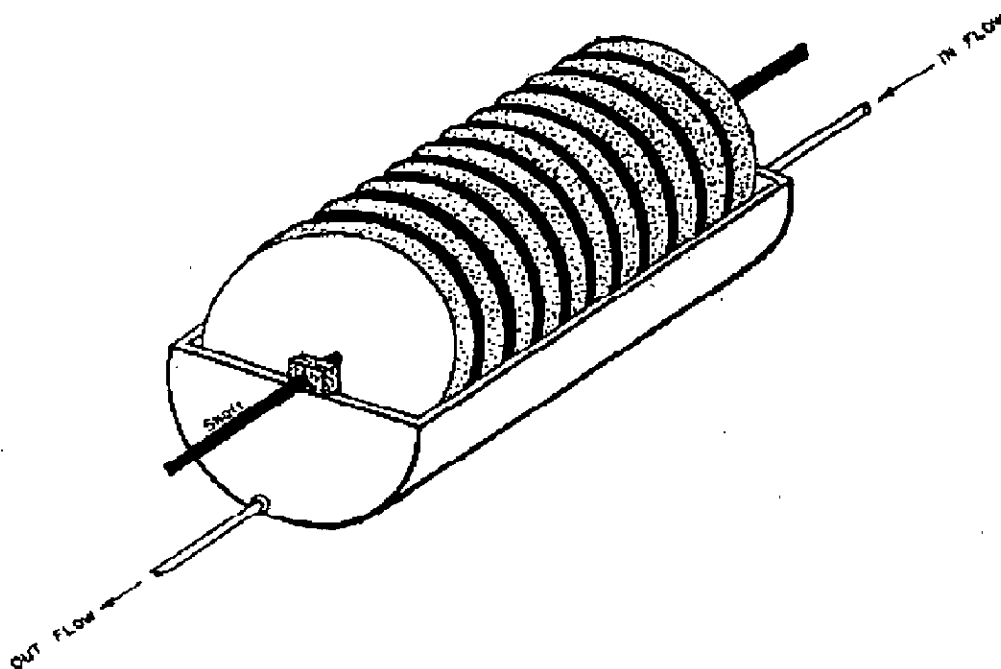
Figure 2.4. Diagram of a biodisk.

Table2.5: Typical design information for rotating biological contactors

Parameter	Unit	Treatment level		
		BOD removal	BOD removal and nitrification	Separate nitrification
Hydraulic loading	$m^3/m^2.d$	0.08-0.16	0.03-0.08	0.04-0.10
Organic loading	gsBOD/ $m^2.d$ gBOD/ $m^2.d$	4-10 8-20	2.5-8 5-16	0.5-1.0 1-2
Maximum 1st stage organic loading	g sBOD/ $m^2.d$ g BOD/ $m^2.d$	12-15 24-30	12-15 24-30	
NH$_3$ loading	g N/ $m^2.d$		0.75-1.5	
Hydraulic retention time	h	0.7-1.5	1.5-4	1.2-3
Effluent BOD	mg/L	15-30	7-15	7-15
Effluent NH$_4$-N	mg/L		<2	1-2

2.1.4. Biodrum

Figure 2.5 shows a schematic of a biodrum. Biodrums look and operate similar to a biodisk except the disks are replaced by a cylindrical drum. The cylindrical drum surface is porous, typically some type of mesh material, and the drum is filled with some type of solid media having a high specific surface area (area of all of the pieces of media in the drum) per unit volume. Plastic media, such as plastic rings or balls, are usually used as media rather than rock (which is heavy) to reduce drum weight and, hence, the structural support needed for the drum.
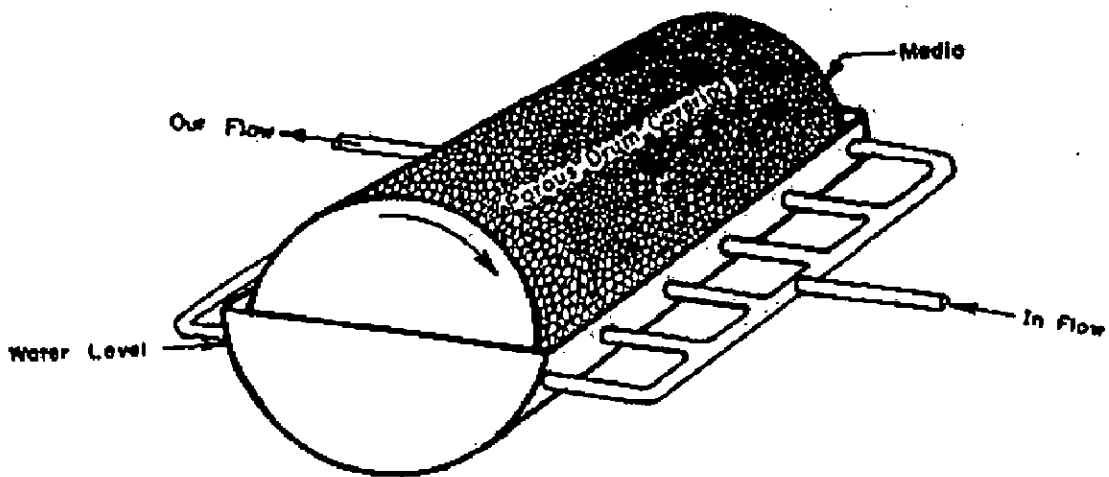
Figure2.5. Biodrum schematic diagram.

2.1.5. Fluidized Beds

Figure2.6. Shows a schematic of fluidized bed filter. The filter consists of a closed container that is partially filled with a particulate media, typically sand. Wastewater enters the filter through the bottom, passes through a distribution plate, moves through the media and exits from the top of the filter. The distribution plate serves two functions; 1) it supports the media and prevents it from clogging the inlet when the filter is not operating, and 2) it helps distribute the wastewater evenly across the horizontal area of the filter. During operation sufficient water flow is maintained to suspend the media particles in the upward flow. This is called fluidizing the bed and is the reason these filters are referred to as fluidized beds. Too low a water flow rate will not fluidize the

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bed, while too high a flow rate will flush the media out of the filter. Nitrifying bacteria grow on the fluidized particles and remove ammonia as it moves past.
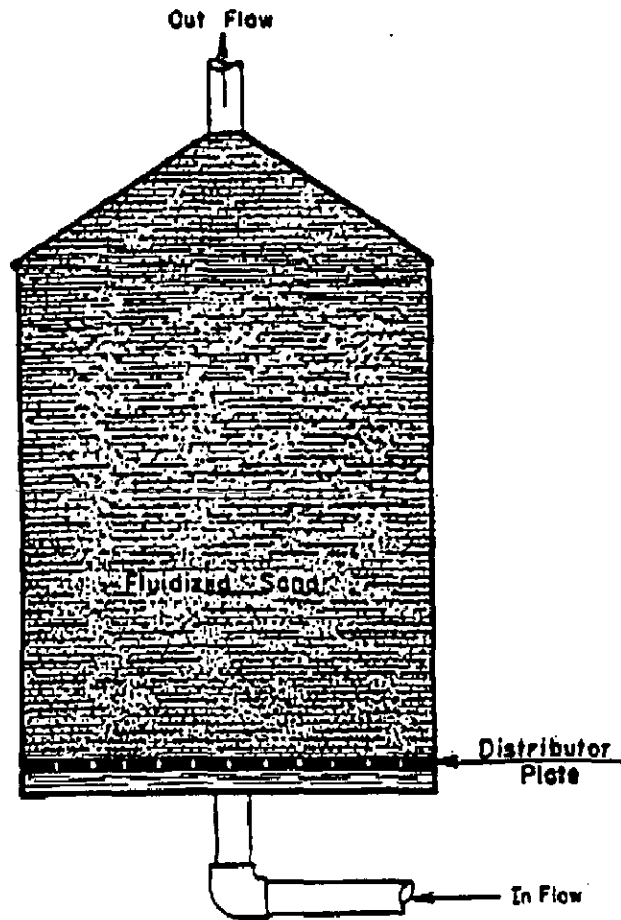
Figure2.6. Schematic diagram of a fluidized bed biofilter.

Successful resolution of environmental protection problems requires the development of new intensive biological technologies. Biofilm processes offer successful technological solutions for the new challenges facing the water industry for compactness, high specific conversion rates, and stable operation. Various innovative biofilm processes have been developed during the past decades for both water and wastewater treatment. Their main advantages could be summarized as follows:

2.2. ADVANTAGES OF BIOFILTERS

2.2.1. Concerning Treatment Performances

1. Simultaneous biological treatment and suspended solids removal (submerged granular biofilters).

2. High biomass concentrations through the ability to use small granular media (submerged granular biofilters, mobile and fluidized beds), high solid hold-up (fluidized beds), and moderate shear stress (air-lift circulating beds, two-phase liquid-solid fluidized beds).

3. Higher biomass activity through simple, effective control of biofilm thickness (three-phase reactors), high biomass retention times, biochemical reactions accelerated by better phase mixing, and a larger surface area for mass transfer (expansion or turbulence of the support media).

4. Better mass transfer due to fewer limitations of external liquid/biofilm surface diffusion (turbulence, high liquid velocity), removal of internal diffusion limitations in the biofilm (thin biofilms), high transfer coefficients similar to those in tower bioreactors (three-phase fluidized beds, turbulent beds, air-lift circulating beds).

5. Stable operation with variations in substrate and toxin concentrations, temperature and hydraulic loads (in particular the turbulent and air-lift circulating beds).

2.2.2. Concerning Design and Operation

1. No sludge recycling and bulking problems.

2. Design without complex technical devices: (a) easier effluent distribution (turbulent beds, air-lift circulating beds); (b) simple and economical aeration system (draft-tube air-lift reactors); (c) auto control of biofilm thickness (three-phase biofilm reactors).

3. Higher aeration efficiency (tall reactors).

4. No backwashing requirement (Three-phase biofilm reactors).

5. Compactness and no noise and odor emissions (closed biofilm reactors).

The greater activity of the fixed biomass and its stable operation with variations in operating and environmental conditions are a unique advantage specific to advanced biofilm processes. Biofilm thickness control has been found to be an important parameter ensuring high efficiency of advance biofilm processes.

2.3. COMPARISON OF FILTER TYPES

2.3.1. Oxygen Supply

The water passing through the filter is the only oxygen source for the bacteria in a submerged filter. This is a major design constraint on submerged filters, because water flow rate is often determined by the bacteria's oxygen demand. Filter oxygen demand is high, sometimes exceeding that of the cultured crop. Oxygen supply in trickling filters, biodisks, and biodrums is primarily from the air. Air contains 210,000 ppm of oxygen while cool, oxygen saturated water contains less than 15 ppm of oxygen. This large oxygen concentration difference between air and water is why it is much easier to supply filter oxygen demands from air contact than by water flow. Fluidized bed filters and bead filters require a relatively high water flow rate to fluidize the bed. Thus, the water flow is usually more than sufficient to supply the needed oxygen.

Oxygen availability to bacteria in rotating biological contactors (RBC's), including biodisks and biodrums, depends on rotational speed of the RBC. Selection of proper rotational speed will assure that the bacteria do not dry out while out of the water, nor do they run out of oxygen while they are in the wastewater. Maximum RBC rotational speed is limited by the bacteria scour velocity. At some velocity, the scour velocity, friction between the water and the media is great enough to strip the bacteria layer off the filter media. Obviously, peripheral disk or drum velocities that exceed the scour velocity will destroy the nitrifying capability of the RBC.

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2.3.2. Energy Usage

Energy requirements of biofilters are an important concern in aquaculture. Energy requirements in submerged and trickling filters are primarily due to pumping water vertically into or out of the filter. Submerged filters can, if designed correctly, operate with from less than one to a few psi (pounds per sq inch) pressure drop across the filter. Trickling filters usually require pumping the water the full height of the filter. Thus, the taller the filter the more energy consumed during operation.

Energy consumption in RBC's is essentially the power required to rotate the RBC. The faster the RBC is rotated, the higher the energy consumption. Increased rotational speed generally increases mixing in the tank containing the RBC. Increased mixing is sometimes desirable because it increases aeration and/or suspension of solids. However, increased mixing increases energy consumption by the RBC. Thus, a design compromise must be made between increased mixing and/or aeration by the RBC and minimizing energy consumption. The pressure loss across an RBC is very low, usually in the range of 1 inch or less of water.

Fluidized bed filters require relative high water velocities to fluidize the media. Energy loss due to the water flowing through a pipe or filter increases with the square of the velocity. Thus, doubling the water velocity through the same pipe increases the energy loss by four times. A similar energy loss is experienced when water velocity through a filter increases. Thus, a designer must balance energy usage against other desirable features of a specific filter.

Bead filters generally have fairly high water velocities through them. Thus, energy consumption in these filters is primarily due to pressure loss through the bead bed.

2.3.3. Clogging

Filter clogging is undesirable, because it restricts water flow through the filter. Restricted water flow reduces filter ammonia removal capacity, may cause the filter to run over, and almost surely will cause oxygen starved areas to develop in the filter. Oxygen starved, anaerobic, areas produce hydrogen sulfide and other toxic and smelly compounds that can cause direct fish kills in the system. Clogging also increases energy loss across the filter which can lead to increased operating costs.

Clogging is caused by an accumulation of organics, dead bacteria, and other particulate debris in the porous passages in the filter. Downflow submerged biofilters are probably most subject to clogging of any of the biofilter designs. Upflow submerged filters and bead filters exhibit somewhat less clogging followed in order by fluidized beds, biodrums, and biodisks. Upflow and downflow submerged filters, bead filters, and fluidized bed filters are designed to facilitate periodic backwashing to remove the accumulated particulates. Biodrums and biodisks rarely clog.

2.4.   BIOFILTER DESIGN

Biofilter design requires some knowledge of the other components of the culture system. For example, what aeration system, what solids removal methods, and what arrangement of the system components will be used in the overall system. This data impacts on the operating conditions of the biofilter and will, thus, influence its design.

There is also a body of data needed that details the water quality requirements acceptable to the species being cultured. Acceptable ranges of pH, temperature, ammonia concentration and other variables must be known. The largest weight of fish the filter will support at any time during the life cycle of the crop must be determined. Feed to be used and feeding rates anticipated, water temperature and range of water temperatures expected, and the range of oxygen demand by the fish all need to be determined prior to designing a biofilter. Waste production rates by the particular fish species are also needed for the range of fish sizes expected in the culture system. This should include solids production as well as ammonia production.

Design of any filtration system is based on the principle that the filter must remove wastes at or above the maximum rate at which the crop produces them. If the production system has sufficient volume of water in it, there is some potential for short term (i.e., a few hours) waste removal rates to be slightly less than the hourly maximum production rate. However, filters should almost always be designed for the maximum short term ammonia production rates.

2.4.1   Design of Innovative Biofilters: The optimum design of biofilters depends on numerous factors including the type of wastewater (composition, variability, and

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treatability), type of reactor and biofilm support media, existing treatment standard, pretreatment processes, environmental conditions (temperature, oxygen concentration), as well as soil constraints, energy consumption, and other specific local conditions. The major factors influencing biofilm reactor design are interrelated and have an impact on capital and operating costs. Taking into account the highly dynamic development of advanced biofilm processes, as well as the specificities of each application for water or wastewater treatment in given local conditions, direct application of the reported values for design purposes is not recommended.

2.5. BIOFILTER MODELING:

Generally, two main parts can be distinguished in a model of a packed biofilter:

1. A reactor model (hydrodynamic aspect);
2. A biofilm model with substrate uptake, product formation and biomass development.

The biofilter should, rigorously, be described as a series of completely mixed tanks or as plug-flow reactor with axial dispersion model. Experimental hydrodynamic studies on a biological filter showed that the axial dispersion may be neglected especially for anaerobic reactions: the filter was described by a series of 16 to 60 (for anaerobic treatment) and 11 to 34 (for aerobic treatment) completely mixed tanks. This number, which depends on the experimental conditions (aerobic or anaerobic reactions, air/water flow-rate ratio, degree of clogging of the filter....), is fairly high and we may consider that the liquid is in plug flow.

For biofilm modeling, four steps are generally considered:

1. Diffusion of substrates through the liquid film layer around the biofilm to be liquid/biofilm interface.
2. diffusion of substrates through the biofilm;

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3. biological reaction and

4. biofilm detachment

A material balance is written for each component involved in the biological reaction or filtration process for a liquid in plug flow:

accumulation = input - output ± reaction,

$$\frac{\partial([]dV)}{\partial t} = Q([]_z - []_{z+dz}) + v_r dV$$

The problem to be solve may be written in vectorial form.

$$D(s,t)\frac{\partial s}{\partial t} = f(s,t,u,p) + g(s,t,u,p)\frac{\partial s}{\partial z}$$

(with appropriate initial and boundary conditions)

And can be solved by using various numerical methods available.

2.5.1. **Problems in Biofilter modeling:** The major problems in biofilm modeling are not the unavailability of more or less sophisticated mathematical tools. They result from the lack of correlations able to produce values of the diffusion coefficients, the biological kinetic parameters and the biofilm thickness as a function of the operating conditions and reactor characteristics; from the lack of capacity to relate the composition and structure of the microbial film, particularly the density and spatial distribution of active cells, to the conditions under which the biofilm was formed; and from the lack of accurate information on the biomass yield in the biofilm. Obviously, all this implies a deeper knowledge of the microbial metabolism inside the biological matrix, including a better understanding of the physiological state of the micro-organisms and their kinetics in the specific micro-environment that surrounds them in a biofilm. The concurrent efforts of both engineering science (to develop semi empirical models that relate intrinsic parameters to external operating and design variables) and biological science (to shed light on the behavior of micro-organisms in attached biomass systems) are clearly needed.

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2.6   CONCLUDING REMARKS

In this chapter we have discussed about various types of biofilters that are currently employed in wastewater treatment technologies. Also design criteria for some biofilter processes have been presented. Various advantages of the biofilters has been listed. Some problems that will be encountered in the modeling of biofilters have been briefly discussed.

LITERATURE REVIEW

To evaluate the performance of a biofilter, a number of modeling studies have been conducted. This chapter presents the models developed by the different researchers for the performance of the biofilters with possible modeling and experimental conclusion to assist further research in this novel technology.

J.Park et al (2002): A pilot scale biofilter pretreatment – microfiltration system (BF-MF) was operated to investigate the effect of biofilter treatment in fouling reduction of microfiltration. Biofiltration was expected to reduce the membrane fouling by removal of turbidity and metal oxides. The hollow-fiber MF module with a nominal pore size of 0.1 μm and a surface area of $8m^2$ was submerged in a filtration tank and microfiltration was operated at a constant flux of 0.5 m/d. Biofiltration using polypropylene pellets was performed at a high filtration velocity of 320 m/d. Two experimental setups composed of MF and BF/MF, i.e. without and with biofilter pretreatment, were compared.

Throughout the experimental period of 9 months, biofilter pretreatment was effective to reduce the membrane fouling, which was proved by the result of time variations of transmembrane pressure and backwash conditions. The turbidity removal rate by biofiltration varied between 40% to 80% due to the periodic washing for biofilter contactor and raw water turbidity.

In addition to turbidity, metals, especially Mn, Fe and Al were removed effectively with average removal rates of 89.2%, 67.8% and 64.9%, respectively. Further analysis of foulants on the used membranes revealed that turbidity and metal removal by biofiltration was the major effect of biofiltration pretreatment against microfiltration fouling.

Table 3.1.: Average concentration of metals after biofiltration

Metal	Unit	Raw water	Biofiltration filtrate
Ca	Mg/L	21.57	21.52
Na		10.52	10.51
Mg		4.71	4.68
K		3.22	3.22
Si		8.06	7.84
Al		0.28	0.1
Fe		0.32	0.1
Mn	μg/L	34.2	3.7
Cu		7.8	6.7

P.G.CHUNG et al(1996): a biofilter process using a spongy media was operated to treat artificial raw water which has similar characteristics to inflow for the use of public water supply. The growth of biofilm and the increase of specific gravity lowered the expansion rate of spongy media. The fluidized biofilter process was likely to behave as a fixed film type of reactors, but the excessive headloss, clogging, and channeling problems, which are known as a major concern in the operation of fixed film process, were not observed throughout the entire operation period.

There are several empirical models which have been used to model the fixed film process. Velz (1948) was the first engineer who tried to describe the behavior of the fixed film process. Velz's equation states that

$$S_e/S_0 = \exp\left[-k\ L/v^n\right] \qquad \text{------------------------------ (1)}$$

Where S_e is an effluent BOD_5 concentration (mg/L), S_0 is an influent BOD_5 concentration (mg/L), k is a first order reaction constant (m^{-1}), L is an effective depth of the column

(m). Velz's equation assumes that the removal of substrate is first order. It did not consider the flow rate. Thus, Velz's equation would be limited to one flow rate.

Eckenfelder(1961) has explicitly accounted for the effects of flow rate

$$S_e/S_0 = \exp[-k\ L/v^n] \quad\text{------------------------} \quad (2)$$

Where v is a hydraulic loading rate applied to the biofilter, which can be obtained by dividing the influent flow rate (Q) plus recycle flow (Q_r) with a surface area of biofilter column (A_f) $(m^3/m^2/min)$, n is a parameter which is dependent on the specific media used, and k is a pseudo rate constant(m^{-1}). Equation (2) has been widely used in designing the trickling filter for the wastewater treatment during the last 30 years.

For evaluating the parameters involved in Equation (2) from the experiment, k/v^n was lumped as a single parameter, K. The lumped reaction constant, K , can be obtained by plotting the different filter depths (L) versus the corresponding values of $\ln(S_e/S_0)$.

$$\ln(S_e/S_0) = -k/v^n L = -KL \quad\text{---------------------------} \quad (3)$$

Also, individual parameters involved in Equation (2) can be separately evaluated by taking the natural logarithm to each side of $K = k/v^n$:

$$Ln[K] = \ln[k] - n\ \ln[v] \quad\text{----------------------------} \quad (4)$$

Plotting the ln[v] versus the ln [K] values obtained from Equation (3) gives the estimates of slope and interception from the linear curve, which is numerically equal to n and k value, respectively.

In this study the Eckenfelder model was used to analyze the results of laboratory scale biofilter operation. The reaction constant in Equation (3) and (4) was graphically

evaluated. The evaluated k and n values are 0.089 min^{-1} and 0.46, respectively. The completed form of Equation (2) can be given by

$$S_c/S_0 = \exp [-0.089(L/v^{0.46})] \qquad \text{------------------------ (5)}$$

X. LE TALLEC et al (1999). One of the most important operating parameters for the operation and design of biofilters is the headloss due to clogging of the system leading to a semi-continuous operation with filtration cycles and backwashes. Some basic aspects of the filtration operation have been studied. The work consists in understanding and modeling the clogging phenomena due to the suspended solids retention and validating the simulation results by calibration with experimental and full-scale results.

Tracer experiments allowed us to simplify the hydrodynamics within the Biofilters into a plug-glow reactor with axial diffusion. Mass balances for the suspended solids have been therefore written accordingly, including solids retention represented as a mass transfer from the liquid to the solid phase. This affects the porosity of the system, leading on one hand to a modification of the filtration coefficient (responsible for the transfer of SS from liquid to "solid" phase) and on the other hand to an increased clogging measured by the headloss in the system.

The Kozeny-Carman equation could successfully be used and a linear relationship between the filter coefficient and the water porosity could be validated. Experimental work has been conducted to calibrate the model and validations from pilot scale unit to full-scale plant are shown.

J.Jacob et al (1997). A general approach for modeling and simulation of biofilters in transient states is presented. The resulting set of partial differential algebraic equations (PDAE) is then solved using an extension of the differential –algebraic philosophy coupled with method of lines.

In most biofilter models, diffusion phenomena are taken into account and described by Fick's law. From a theoretical point of view, the diffusion is a phenomenon, which occurs perpendicularly to the liquid flow through a flat surface. In biological filtration,

the biofilms are very irregular and filamentous which accords poorly with the diffusional theory hypothesis. Furthermore, experimental studies on aerobic and anaerobic biofilms show that the substrate removal reaction occurs only at the edge of the biofilm in a very thin part of it- the active thickness is estimated at about 10 μm where as the biofilm may reach 500 μm. Thus, the reaction may be considered as a surface reaction. An approach based on the concept of active/deactivated biomass (M_a/M_d) was used. The principle is described below.

- The active microorganisms are responsible for substrate degradation and are characterized by a specific growth rate μ_0:

$$\mu_0 = \mu_{max}\left(\frac{S_D}{S_D + K_D}\right)\left(\frac{S_A}{S_A + K_A}\right)$$

- The deactivated microorganisms do not play any role in substrate degradation (even though they might maintain their enzymic activity) but continue to play a role in filter clogging.

- The total biomass is defined as the sum of the two types of biomass

$$X_B = X_A + X_D$$

- An intrinsic kinetic (without considering deactivation of the active biomass) is defined:

$$\left(\frac{\partial X_A}{\partial t}\right)_i = r_a = \mu_0 X_A$$

A material balance is written for each component on an elementary volume, for a liquid in plug-flow inside the biofilter:

accumulation = input - output $\pm$ reaction,

$$\frac{\partial([\,]dV)}{\partial t} = Q([\,]_z - [\,]_{z+dz}) + \nu r dV$$

Where ν is the stoichiometric coefficient for the component involved in reaction r.

These material balances are combined with space balance- the variations of the void fraction (of porosity ε) are due to the growth of total biomass and the retention of suspended particles:

$$\frac{\partial \varepsilon}{\partial t} = -\left(\frac{1}{d_{cell}} \frac{\partial X_B}{\partial t} + \frac{1}{d_{part}} \frac{\partial X_{Mr}}{\partial t} \right)$$

Basic assumptions of the model:

- The liquid is in plug flow.

- The liquid flow- rate is supposed to be constant inside the filter but variations in feed flow-rate are taken into account.

- Suspended particles in the influent are taken into account.

- Filter clogging is taken into account.

- Diffusion phenomena are not taken into account.

- The gaseous phase is not taken into account.

- The initial amount of biomass is uniform in the filter.

- Decay of biomass is neglected.

- Detachment of biofilm and retained particles is neglected (laminar flow).

- Temperature and pH (close to 7) are constant in the filter.

System of equations for M_a/M_d approach:

Total biomass:
$$\frac{\partial X_B}{\partial t} = \mu_{max} \left(\frac{S_D}{S_D + K_D} \right)\left(\frac{S_A}{S_A + K_A} \right) X_A$$

Active biomass:

$$\frac{\partial X_A}{\partial t} = \mu_{max} \left(\frac{S_D}{S_D + K_D} \right)\left(\frac{S_A}{S_A + K_A} \right) X_A \left(1 - \frac{X_A}{X_{Amax}} \right)$$

Retained particles:
$$\frac{\partial X_{M_r}}{\partial t} = \frac{QkX_{M_r}}{\Omega}$$

Electron donor:
$$\frac{\partial (\varepsilon S_D)}{\partial t} = -\frac{Q}{\Omega} \frac{\partial S_D}{\partial z} - v_D \mu_{max} \left(\frac{S_D}{S_D + K_D} \right)\left(\frac{S_A}{S_A + K_A} \right) X_A$$

Electron acceptor:
$$\frac{\partial (\varepsilon S_A)}{\partial t} = -\frac{Q}{\Omega} \frac{\partial S_A}{\partial z} - v_A \mu_{max} \left(\frac{S_D}{S_D + K_D} \right)\left(\frac{S_A}{S_A + K_A} \right) X_A$$

Ammonia (or nitrates in case of denitrification):
$$\frac{\partial (\varepsilon S_N)}{\partial z} = -\frac{Q}{\Omega} \frac{\partial S_N}{\partial z} - v_N \mu_{max} \left(\frac{S_D}{S_D + K_D} \right)\left(\frac{S_A}{S_A + K_A} \right) X_A$$

Suspended particles: $\dfrac{\partial(\varepsilon X_{M_i})}{\partial t} = -\dfrac{Q}{\Omega}\dfrac{\partial X_{M_i}}{\partial z} - \dfrac{QkX_{M_i}}{\Omega}$

Porosity: $\dfrac{\partial\varepsilon}{\partial t} = -\dfrac{\mu_{max}}{d_{cell}}\left(\dfrac{S_D}{S_D + K_D}\right)\left(\dfrac{S_A}{S_A + K_A}\right)X_A - \dfrac{QkX_{M_i}}{d_{part}\Omega}$

Initial and boundary conditions:

$X_B(t = 0) = X_{A0}$

$X_A(t = 0) = X_{A0}$

$X_{MI}(t = 0) = 0$

$S_D(t = 0) = S_D(z = 0) = S_{D(input)}$

$S_A(t = 0) = S_A(z = 0) = S_{A(input)}$

$S_N(t = 0) = S_N(z = 0) = S_{N(input)}$

$X_{MI}(t = 0) = X_{MI}(z = 0) = X_{MI(input)}$

$\varepsilon(t = 0) = \varepsilon_0$

The equations describing filter behavior lead to partial differential algebraic system (PDAE) which may be written in vectorial form with adequate initial and boundary conditions:

$$D(s,t)\dfrac{\partial s}{\partial t} = f(s,t,u,p) + g(s,t,u,p)\dfrac{\partial s}{\partial z}$$

Different numerical methods may be used to solve this kind of system. Bearing in mind the generalization, a numerical strategy issued from the solving of mixed differential and algebraic equations system (DAE) coupled with the method of lines with fixed grid discretization has been implemented.

RAYMOND M. HOZALSKI and EDWARD J.BOUWER (2001a): A numerical model was developed to simulate the non-steady-state behavior of biologically active filters used for drinking water treatment. The biofilter simulation model called "BIOFILT" simulates the substrate (biodegradable organic matter or BOM) and biomass (both attached and suspended) profiles in a biofilter as a function of time. One of the innovative features of BIOFILT compared to previous biofilm models is the ability to simulate the effects of a sudden loss in attached biomass or biofilm due to filter backwash

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on substrate removal performance. A sensitivity analysis of the model input parameters indicated that the model simulations were most sensitive to the values of parameters that controlled substrate degradation and biofilm growth and accumulation including the substrate diffusion coefficient, the maximum rate of substrate degradation, the microbial yield coefficient, and a dimensionless shear loss coefficient. Variation of the hydraulic loading rate or other parameters that controlled the deposition of biomass via filtration did not significantly impact the simulation results.

Assumptions of BIOFILT model:

- The media particles and bacteria consist of uniform spheres.

- The biofilm is homogeneous with respect to population, thickness, and coverage within a given filter segment (Δx).

- A single substrate is both diffusion and reaction limiting in the biofilm; and

- Backwashing occurs instantaneously and results in a reduction in biofilm thickness throughout the bed depth.

- There is no mixing of filter media during backwashing.

- Effects of dispersion, growth and decay on transport of suspended biomass are neglected.

- The substrate concentration profiles within the biofilm are at steady state while both the biofilm thickness and substrate concentrations along the length of the reactor are not at steady state.

Model equations:

$$\frac{\partial S}{\partial t} = D\frac{\partial^2 S}{\partial x^2} - v\frac{\partial S}{\partial x} - \frac{kSX_{susp}}{K_s + S} - \frac{a}{\varepsilon}J_f$$

$$\frac{\partial X_{susp}}{\partial t} = -v\frac{\partial X_{susp}}{\partial x} + \frac{aX_f\sigma}{\varepsilon}L_f - \frac{X_{susp}\beta}{\theta\varepsilon}$$

$$\frac{\partial L_f}{\partial t} = \frac{YJ_f}{X_f} + \frac{X_{susp}\beta}{X_f a\theta} - b_{tot}L_f$$

Where D^1 is the dispersion coefficient (L^2/T)

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v is the fluid velocity (L/T)

t is time (T)

x is the distance along the biofilter length (L)

k is the maximum rate of substrate utilization (M_S/M_XT)

K_S is the Monod half-velocity coefficient (M_S/L^3)

X_{susp} is the suspended cell concentration (M_X/L^3)

a is the specific surface area of the media (1/L)

J_f is the flux of substrate into the biofilm (M_S/L^2T)

ε is the bed porosity

β is the filtration efficiency (unitless)

θ is the empty-bed contact time (T)

σ is the biofilm shear loss coefficient (1/T)

L_f is the biofilm thickness

Y is the microbial yield coefficient

b_{tot} is the overall loss rate of bacteria due to both decay and fluid shear (1/T)

X_f is the bacterial density in the biofilm (M_S/L^3)

Boundary conditions and initial conditions:

BC 1: $vS_0 = vS_{x=x} - D \cdot \dfrac{dS}{dx}$ For x=0, $t \geq 0$

BC 2: $\dfrac{dS}{dx} = 0$ For x=L_b, $t \geq 0$

IC 1:   S = S_0 for $0 \leq x \leq L_b$, t = 0

IC 2: X_{susp} = 0 for $0 \leq x \leq L_b$, t = 0

IC 3: L_f = 0 for $0 \leq x \leq L_b$, t = 0

RAYMOND M. HOZALSKI and EDWARD J.BOUWER (2001b): A biofilter model called "BIOFILT" was used to simulate the removal of biodegradable organic matter (BOM) in full-scale biofilters subjected to a wide range of operating conditions. Parameters that were varied included BOM composition, water temperature (3.0 –

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22.5^0C), and biomass removal during backwashing (0-100%). Results from biofilter simulations suggest a strong dependence of BOM removal on BOM composition. BOM with a greater diffusivity or with faster degradation kinetics was removed to a greater extent and also contributed to shorter biofilter start-up times. In addition, in simulations involving mixtures of BOM (i.e. readily degradable and slowly degradable components), the presence of readily degradable substrate significantly enhanced the removal of slowly degradable material primarily due to the ability to maintain greater biomass levels in the biofilters. Declines in pseudo-steady state BOM removal were observed as temperature was decreased from 22.5 to 3^0C and the magnitude of the change was significantly affected by BOM composition. However, significant removals of BOM are possible at low temperatures (3-6 ^0C). Concerning the impact of backwashing on biofilter performance, BOM removal was not affected by backwash resulting in biomass removals of 60% or less. This suggests that periodic backwashing should not significantly impact biofilter performance as observed biomass removals from full-scale biofilters were negligible. In general, the simulation results were in good qualitative and quantitative agreement with experimental results obtained from full-scale biofilters.

P.Viotti et al(2002): Biofiltration is gradually gaining popularity among biological wastewater treatment processes, becoming a valid alternative to the more widespread activated sludge system. In order to understand better the operating conditions that influence the efficiency of such a process, a mathematical model has been developed. It allows the calculation of the COD and $N-NH_4^+$ profiles along the filter height and inside the biofilm and simulates filter clogging due to the biomass growth. The model output has been verified through a series of sensitivity tests and its results have been calibrated considering the results of an experimental campaign conducted on the Biostyr biofiltration unit of the Rome southern municipal wastewater treatment plant.

Model:

Mass transport, diffusion and consumption of substrates in the biofilm

Assumptions:

- The support medium particles are spherical;
- The biofilm is homogeneous and uniform in thickness on a single bioparticle;
- Mass transport is described by Fick's law;
- Biochemical reactions are described by double-saturation Michaelis-Menten kinetics; and
- There are pseudo stead-state conditions.

Equations:

$$\frac{d}{dx}\left[(x+\xi)^2\frac{dC^*}{dx}\right]-\alpha(x+\xi)^2\frac{C^*}{Y_c+C^*}\frac{O^*}{Y_{co}+O^*}\phi_c^2=0$$

$$\frac{d}{dx}\left[(x+\xi)^2\frac{dN^*}{dx}\right]-(1-\alpha)(x+\xi)^2\frac{N^*}{Y_n+N^*}\frac{O^*}{Y_{no}+O^*}\phi_n^2=0$$

$$\frac{d}{dx}\left[(x+\xi)^2\frac{dO^*}{dx}\right]-\alpha k_{01}(x+\xi)^2\frac{C^*}{Y_c+C^*}\frac{O^*}{Y_{co}+O^*}\phi_{co}^2-(1-\alpha)k_{02}(x+\xi)^2\frac{N^*}{Y_n+N^*}\frac{O^*}{Y_{no}+O^*}\phi_{no}^2=0$$

Boundary conditions:

- Biofilm-support medium interface (x=0)

$$\frac{dC^*}{dx}=0$$

$$\frac{dN^*}{dx}=0$$

$$\frac{dO^*}{dx}=0$$

- Liquid bulk-biofilm interface (x=1):

$$\frac{dC^*}{dx} = B_{cc}(1 - C^*)$$

$$\frac{dN^*}{dx} = B_{cn}(1 - N^*)$$

$$\frac{dO^*}{dx} = B_{co}(1 - O^*)$$

Filter flow model:

Assumptions:

- Substrates (COD, N-NH$_4^+$) are dissolved in the liquid phase and do not influence the fluid motion;

- Biomass attached to the support medium particles: the quantity of suspended biomass is negligible, and consequently no biodegradation occurs in the liquid phase;

- Movement in the filter is monodimensional;

- Liquid phase moves through the reactor by convection and turbulent diffusion;

- The support medium characteristics are uniform through the bed height;

- Initial porosity is assumed constant through the bed height;

- There are pseudo steady-state conditions;

- Removal kinetics of each substrate are limited by the concentration of the substrate itself and of oxygen; and

- The dissolved oxygen concentration is assumed constant through the bed height. Such an assumption has proved to be close to reality, since measured values of DO concentrations were characterized by negligible variations.

Equations:

$$\frac{dB^*}{d\zeta} - B_0 \frac{d^2 B^*}{d\zeta^2} + \frac{\tau}{C_{bi}} R_{vc} = 1$$

$$\frac{d\Lambda^*}{d\zeta} - B_0 \frac{d^2 \Lambda^*}{d\zeta^2} + \frac{\tau}{N_{bi}} R_{vm} = 1$$

The boundary conditions are

- Base of the filter ($\zeta = 0$):

$$B^* - B_0 \frac{dB^*}{d\zeta} = 1$$

$$\Lambda^* - B_0 \frac{d\Lambda^*}{d\zeta} = 1$$

- End of the filter ($\zeta = 1$):

$$\frac{dB^*}{d\zeta} = 0$$

$$\frac{d\Lambda^*}{d\zeta} = 0$$

C.K.Hope, T.R. Bott (2004): Laboratory biofilters (pilot-scale, 20 l and laboratory-scale, 5 l) were constructed in order to model the bioaccumulation of manganese (Mn) under flow conditions similar to those occurring in biofilters at groundwater treatment sites. The biofilters were operated as monocultures of Leptothrix discophora, the predominant organism in mature Mn oxidizing biofilms. Biologically mediated Mn bioaccumulation was successfully modeled in both filter systems. The data obtained showed that in the small-scale biofilter, the Mn concentrations that gave the highest rate of Mn bioaccumulation, shortest maturation time, highest optical density (biomass) and growth rate were between 2000 and 3000 µg/l. The non-problematic scale-up of the process from the laboratory-scale to the pilot-scale biofilter model suggests that Mn biofilters may be 'seeded' with laboratory grown cultures of L. discophora. By initially operating the

biofilter as a re-circulating batch culture, with an initial Mn concentration of ~2500 µg/l, it is hoped to reduce the filter maturation time from months to days.

D. S. Chaudary et al (2003) 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 main components that are incorporated in the model are (1) substrate in the bulk liquid, (2) biomass suspended in the bulk liquid, (3) substrate diffusion and biodegradation in biofilm, (4) biofilm growth and decay, and (5) change in bed porosity, specific surface area and bed depth.

Substrate in the bulk liquid:

$$\frac{\partial C}{\partial t} = D_{ax}\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - \gamma_{bio} - \gamma_{ads} \qquad \text{-------------- (1)}$$

With initial and boundary conditions

$$C = C_0$$

$$D_{ax}\frac{dC}{dz} = -v(C|_{z=0} - C|_{z=z}) \text{ at } z=0$$

$$\frac{dC}{dz} = 0 \text{ at } z=L$$

The last two terms in equation (1) represents the substrate removal rates by biodegradation and adsorption respectively, and are given by:

$$\gamma_{bio} = k_{max}\left(\frac{C}{K_s + C}\right)X_s$$

$$\gamma_{ads} = (1-\varepsilon)\left(\frac{3N}{4.\pi.R_p^3}\right)$$

Biomass suspended in the bulk liquid:

$$\frac{\partial X_s}{\partial t} = \left(Y\frac{k_{max}C}{K_s + C} - K_{dc} - \frac{\beta}{\theta\varepsilon}\right)X_s + \frac{1-\varepsilon}{\varepsilon}a_f X_f \sigma$$

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With initial and boundary conditions

$X_s = X_{s0}$ at z=0

Biofilm Diffusion and Biodegradation:

$$\frac{\partial S_h}{\partial t} = D_f \frac{\partial^2 S_h}{\partial x^2} - X_f \frac{k_{max}S_h}{K_s + S_h}$$

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

Biofilm growth and decay:

$$\frac{dL_f}{dt} = \int_0^{L_f} \left(\frac{Yk_{max}S}{K_s + S} - b_{ut} \right) dr$$

Change in Bed porosity, Specific surface area and Bed depth:

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

$$a_f' = \frac{3(1 - \varepsilon_0)}{2R_p} \left(1 + \frac{L_f}{R_p} \right) \left[(2 - n)\frac{L_f}{R_p} + 2 \right]$$

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

3.1. Objectives of the study

On the basis of the above literature review, we have aimed the following objectives

- To develop a simple mathematical model for a biofilter,
- To solve the mathematical model by using MATLAB 6.5 software,
- To validate the model with the available experimental results in the literature,
- To study the effect of various parameters on the performance of the biofilter.

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3.2. CONCLUDING REMARKS

In this chapter we have seen various literatures are available in the field of biofilters. Many researchers have worked in the field of mathematical modeling and have developed models by taking different assumptions and also with different objectives. It can be evident by the reviewed literature that a good deal of information can be obtained from the review presented herein. Lastly, the motivation for the present work has been explained.
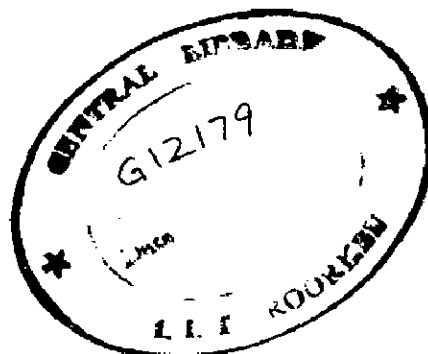
MODEL DEVELOPMENT

INTRODUCTION

This chapter expresses the concern over development of mathematical model for heavy metal removal from wastewater in a biofilter. The water to be treated is sent through a packed bed of support material on which microorganisms grow. The microorganisms remove heavy metals by biological oxidation and accumulation. Model requires kinetic parameters and other physical properties pertaining to separation carried out in biofilter so that solution of model equations may be obtained.

4.1 ASSUMPTIONS

The mathematical model equations are formed on following simplified assumptions:

- Support medium particles are non porous.

- Support medium characteristics are uniform through the bed height.

- Movement in the filter is monodimensional i.e. movement in radial direction is neglected.

- Liquid phase moves through the filter by convection and axial dispersion.

- The biofilm is homogeneous with respect to population, thickness and coverage within a given filter segment.

- Biofilm thickness along the length of the filter is at steady state.

- Biomass is attached to the support medium particles, the quantity of suspended biomass is negligible, and consequently no biodegradation occurs in the liquid phase.

- Biomass loss due to shear is negligible.

4.2 CHOICE OF CONTROL VOLUME

For developing model we divide the length of biofilter L into small elemental length dz and carry out the mass balance around dz. The physical properties are assumed to be constant within the control volume chosen.
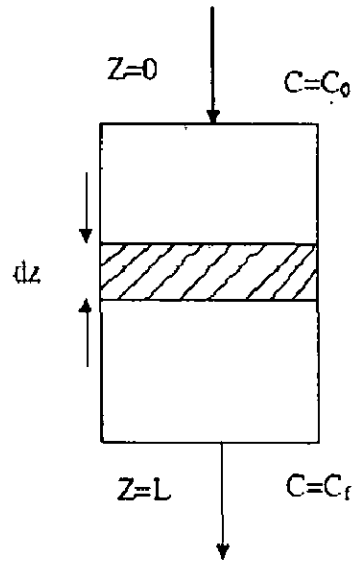

Fig 4.1 Control Volume

4.3 MATERIAL BALANCE

$$\begin{pmatrix} Rate \\ of \\ accumulation \end{pmatrix} = \begin{pmatrix} Rate \\ of \\ input \end{pmatrix}_{con} - \begin{pmatrix} Rate \\ of \\ output \end{pmatrix}_{con} + \begin{pmatrix} Rate \\ of \\ input \end{pmatrix}_{dis} - \begin{pmatrix} Rate \\ of \\ output \end{pmatrix}_{dis} - \begin{pmatrix} Rate \\ of \\ adsorption \end{pmatrix}$$

$$\frac{\Delta C}{\Delta t}\Delta z.S = \left(SvC\big|_z - Sv(C+\Delta C)\big|_{z+\Delta z} \right) + \left(-D\frac{\partial C}{\partial z}\bigg|_z - \left(-D\frac{\partial C}{\partial z}\bigg|_{z+\Delta z} \right) \right) - \frac{\Delta q}{\Delta t} \quad \ldots\ldots(4.1)$$

Dividing with $\Delta z.S$ and $\Delta z \to 0, \Delta t \to 0$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - \frac{\partial q}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.2)$$

Where $D = 1.8d_c v$, d_c is packing material size from Hozalski et al (2001a)

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Boundary conditions

$\{$ Convectional molar flow at $z = 0^-\}$

$\qquad = \{$ Convectional and dispersional molar flow at $z = 0^+\}$

$$vC_{z=0^-}.\Delta z.S = vC_{z=0^+}.\Delta z.S - D.\Delta C.S \dots\dots\dots\dots\dots\dots\dots(4.3)$$

Dividing with $\Delta z.S$ and $\Delta z \rightarrow 0$ simplifies equation (4.3) as follows.

$$vC_0 = vC_{z=z} - D\frac{dC}{dz} \quad \text{For } z = 0, t \geq 0 \dots\dots\dots\dots\dots\dots\dots(4.4)$$

$\{$ Convectional and dispersional molar flow at $z = L^-\}$

$\qquad = \{$ Convectional molar flow at $z = L^+\}$

$$vC_{z=L^-}.\Delta z.S = vC_{z=L^+}.\Delta z.S - D.\Delta C.S \dots\dots\dots\dots\dots\dots\dots(4.5)$$

Since $C_{z=L^-} = C_{z=L^+}$, dividing equation (4.5) with $\Delta z.S$ and $\Delta z \rightarrow 0$ simplifies equation (4.5) as follows

$$\frac{dC}{dz} = 0 \quad \text{For } z = L, t \geq 0 \dots\dots\dots\dots\dots\dots\dots(4.6)$$

4.4 MATHEMATICAL MODEL

The mathematical model comprises of set of mathematical equations, boundary conditions and constitutive relationships. These are presented sequentially in this section.

4.4.1 Mathematical Equations

Model includes two partial differential equations presented by equations (4.7, 4.8). In these equations z, t are independent variables.

$$\frac{\partial C_i}{\partial t} = D\frac{\partial^2 C_i}{\partial z^2} - v\frac{\partial C_i}{\partial z} - \frac{\partial q}{\partial t} \dots\dots\dots\dots\dots\dots\dots(4.7)$$

$$\frac{\partial q}{\partial t} = K(C_i^* - C_i) \dots\dots\dots\dots\dots\dots\dots(4.8)$$

Where C_i is the concentration of heavy metal, z is the length coordinate, t is time;

4.4.2. Boundary conditions

The Dankwerts boundary conditions are used along with initial conditions to solve the proposed mathematical model equations.

$$vC_0 = vC_{z=z} - D\frac{dC}{dz} \quad \text{For } z = 0, t \geq 0 \dots\dots\dots\dots\dots\dots(4.9)$$

$$\frac{dC}{dz} = 0 \quad \text{For } z=L, t \geq 0 \dots\dots\dots\dots\dots\dots(4.10)$$

4.4.3. Initial conditions

$$C = C_0 \quad \text{for} \quad 0 \leq z \leq L, t = 0 \dots\dots\dots\dots\dots\dots(4.11)$$

Table 4.1. Operating conditions for the simulation of biofilter

Name	Parameter specification
Biofilter length (L) (m)	1
Biofilter diameter (D) (mm)	75
Packing type	Pebbles (used as building material)
Packing size (d_c) (mm)	25
Microorganism	L. discophora
Flow rate (Q) (L/min)	4
Initial concentration of metal (µg/L)	5929.5806
Adsorption constant	0.0026

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4.5   CONCLUDING REMARKS

In this chapter detailed derivation of model equations are presented. To derive model we take simplifying assumptions. Those assumptions are also mentioned. Model consists of set of linear coupled partial differential equations, which form an initial and boundary value problem. These equations can be solved by PDE solvers of MATLAB.

RESULTS AND DISCUSSION

5.1 VALIDATION OF MODEL

In this chapter, results of the developed model have been represented and discussed. Our proposed model predicts the concentration profiles of components along the length of the biofilter. The numerically computed results are shown graphically. Developed model has been validated with results given by C.K. Hope, T.R. Bott (2004), L.Travieso et al. (2002) and Nicholas, R.A. et al (2003). Model predictions were in agreement with those given by the C.K. Hope, T.R. Bott (2004), L.Travieso et al. (2002) and Nicholas, R.A. et al (2003). These results are presented graphically.

5.2 STUDY OF REMOVAL OF COBALT

Fig. 5.1 shows cobalt concentration along the length of the biofilter at different times. Fig. 5.2 shows cobalt concentration with time in biofilter at different lengths. Fig. 5.3 shows the variation of the cobalt ion concentration accumulated in the biofilm with increase in operational time of biofilter. As can be seen, in a period of 70 hours, the cobalt ion concentration in the liquid fraction decreased from 3000 to 700μg/l, corresponding to an average efficiency of 81.12%. After 170 hours of operation, the cobalt concentration decreased to 210μg/l and the removal efficiency increased to around 93%. After 200 hours of operational time, the concentration of cobalt decreased to 165μg/l. After that the cobalt concentration remained constant showing that equilibrium concentration has been reached. The maximum removal efficiency of cobalt obtained was 94.5%. A further increase of the operational time did not increase the removal efficiency. The amount of cobalt accumulated in the biofilm at different contact times appears to be a function of the maximum capacity of cobalt biosorption in the surface of the biofilm. The maximum capacity of cobalt accumulation is a function of the initial concentration of this cation.
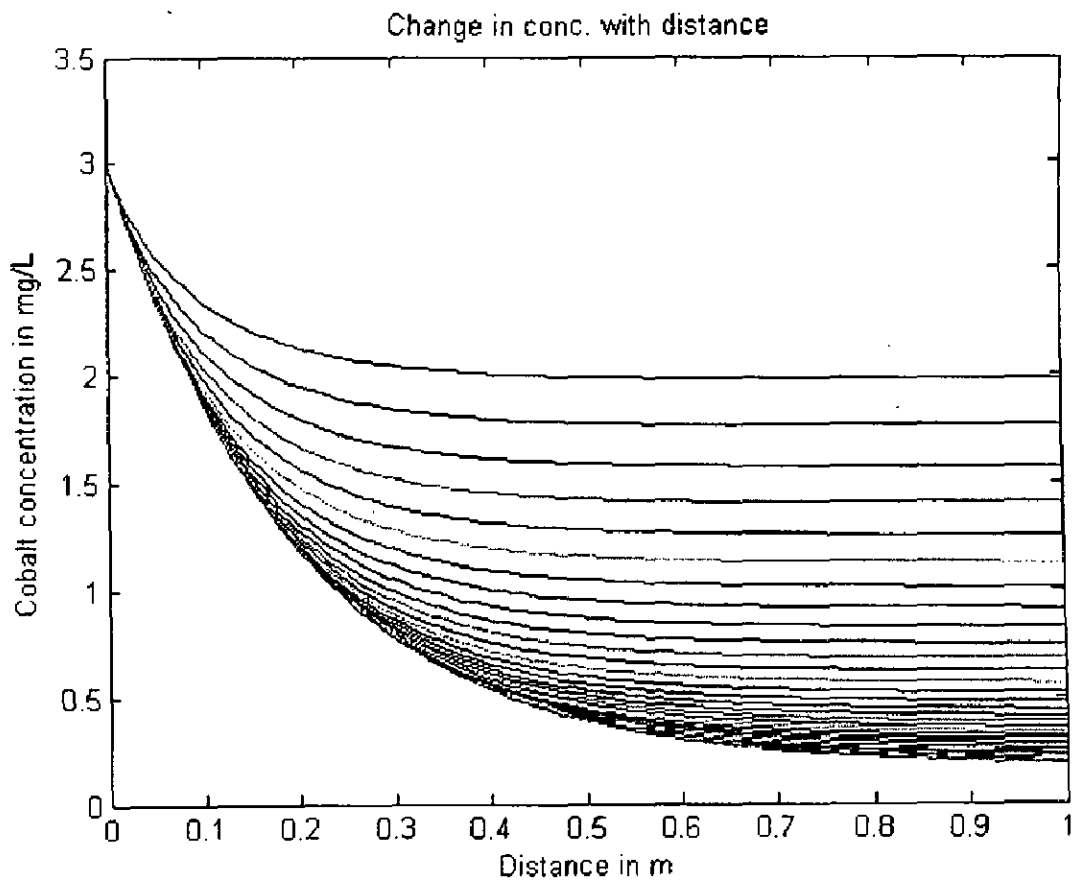
Fig 5.1 Cobalt concentration along the length of the
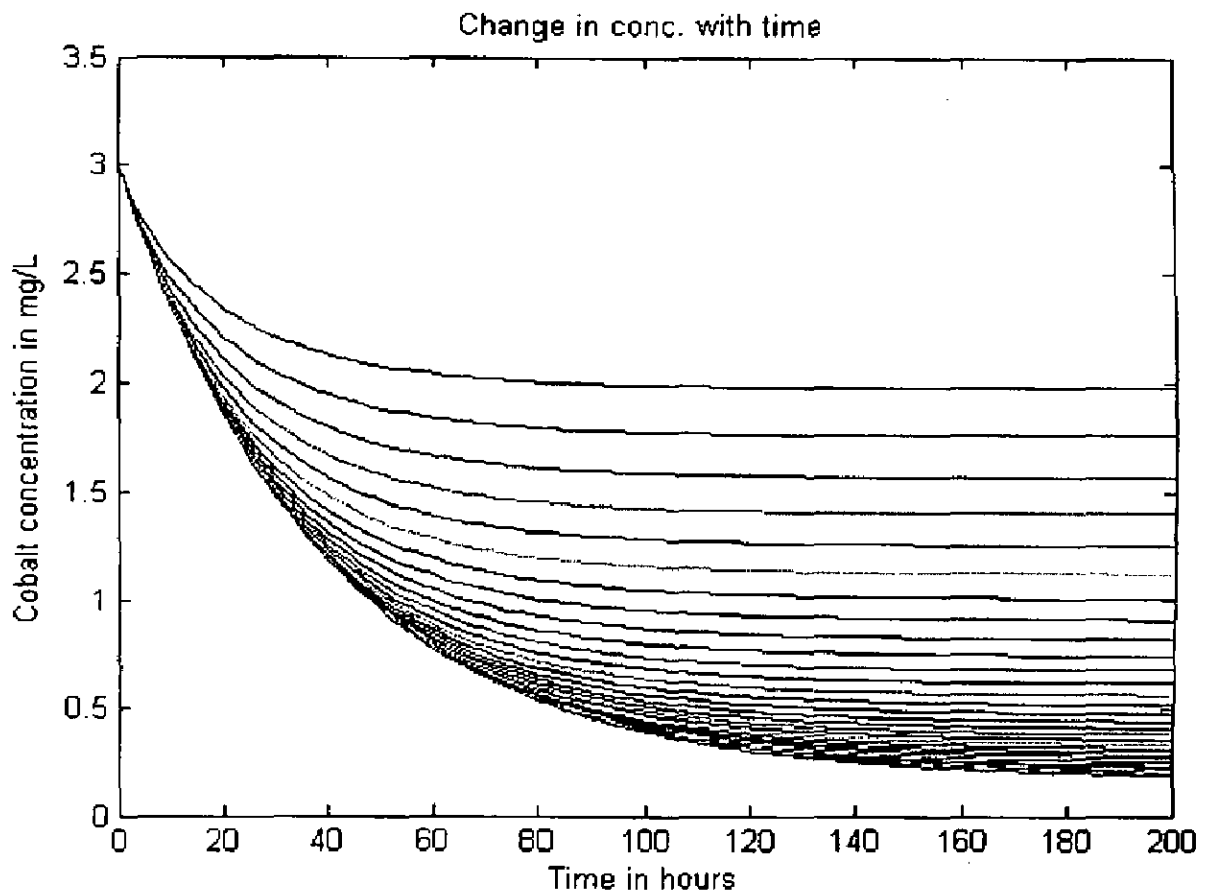biofilter at different times

Fig 5.2 Cobalt concentration with operational time in the
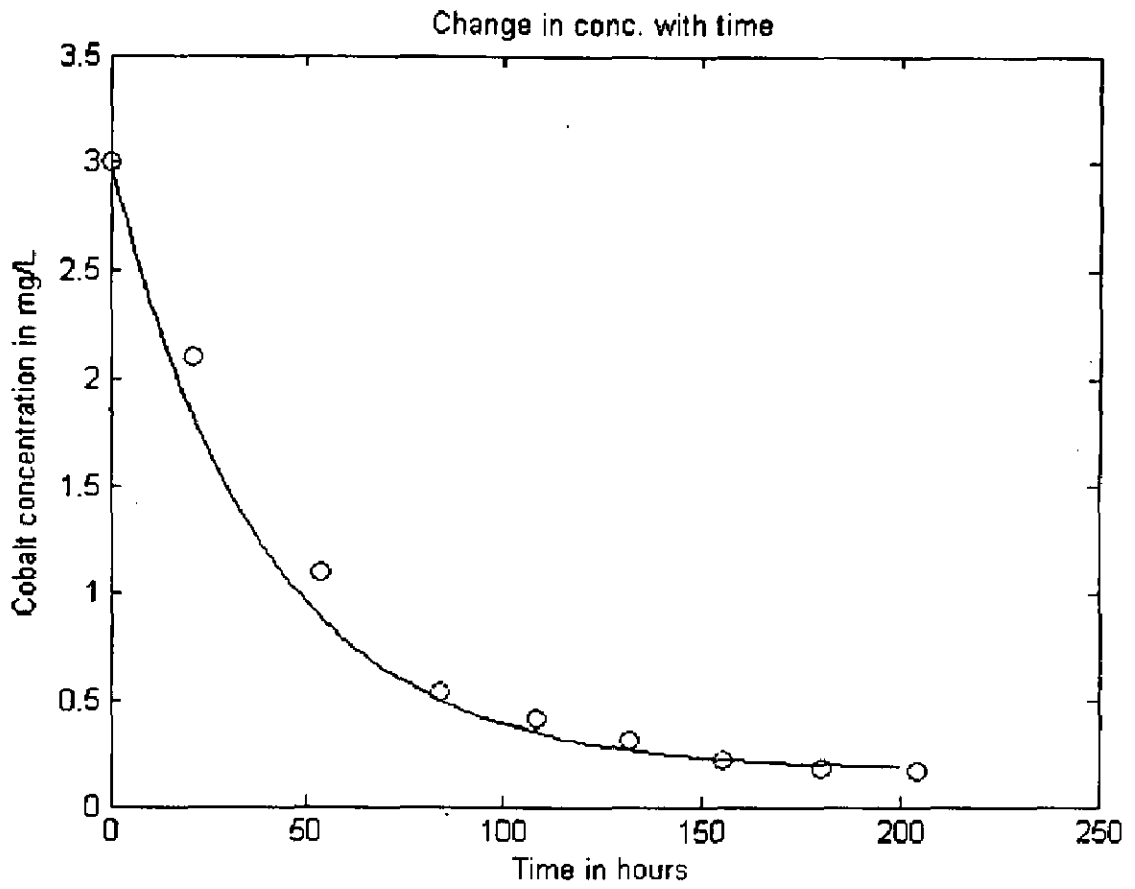biofilter at different lengths.

Change in conc. with time

Fig 5.3 Validation plot for Cobalt concentration in the biofilter.

5.3 STUDY OF REMOVAL OF LEAD

Fig. 5.4 shows lead concentration along the length of the biofilter at different times. Fig. 5.5 shows lead concentration with time in biofilter at different lengths. Fig. 5.6 shows the variation of the lead concentration accumulated in the biofilm with increase in operational time of biofilter. As can be seen, in a period of 70 hours, the cobalt ion concentration in the liquid fraction decreased from 6300 to 3000µg/l, corresponding to an average efficiency of 57.85%. After 170 hours of operation, the lead concentration decreased to 2000µg/l and the removal efficiency increased to around 70.18%. After 250 hours of operational time, the concentration of lead decreased to 900µg/l. After that the lead concentration remained constant showing that equilibrium concentration has been reached. The maximum removal efficiency of cobalt obtained was 94.7%. A further increase of the operational time did not increase the removal efficiency. The amount of lead accumulated in the biofilm at different contact times appears to be a function of the maximum capacity of lead biosorption in the surface of the biofilm. The maximum capacity of lead accumulation is a function of the initial concentration of this cation.
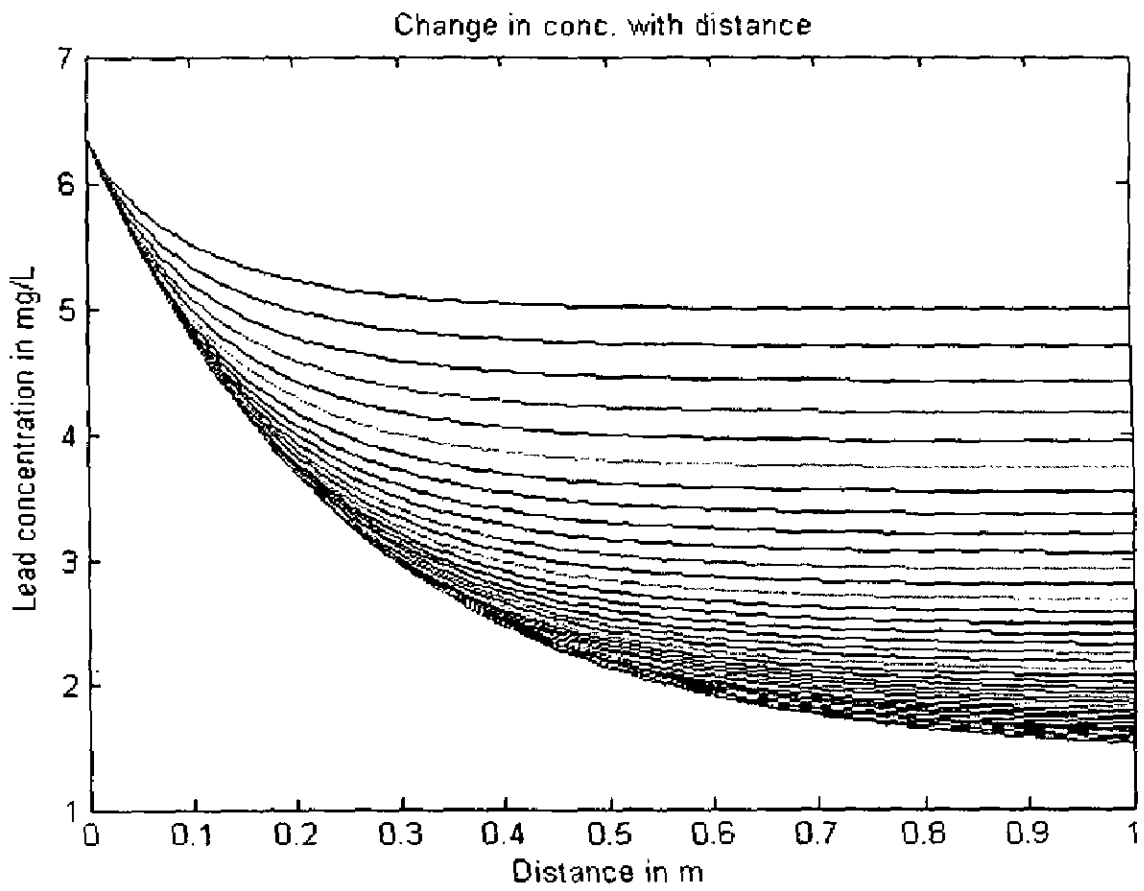
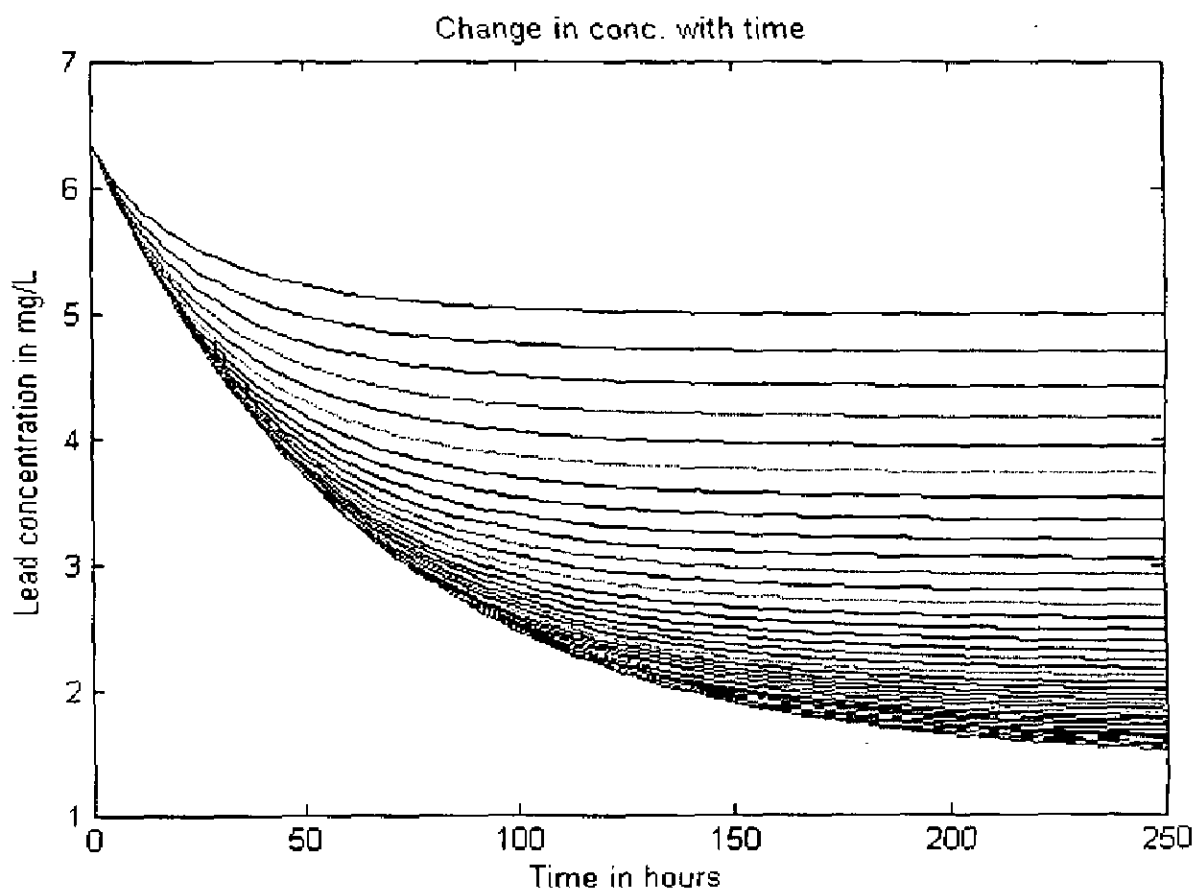**Fig 5.4 Lead concentration along the length of the biofilter at different times**

Fig 5.5 Lead concentration with operational time in the biofilter at different lengths.
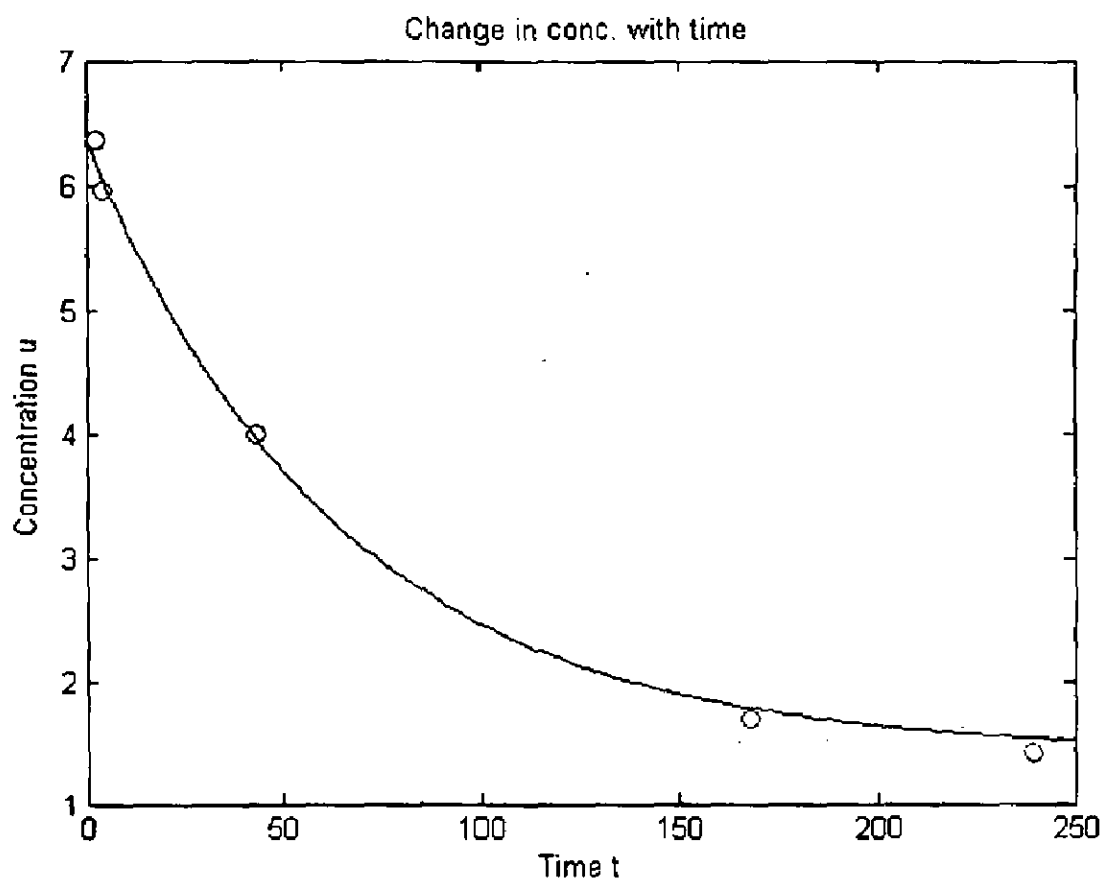
Fig 5.6 Validation plot for lead concentration
in the biofilter.

5.4   STUDY OF REMOVAL OF MANGANESE

The biofilter accumulated Mn, mediated by L. discophora. In this instance (Fig. 5.9) the Manganese concentration decreased from 5929.13 to 2700 µg/L over a period of 150 h. This showed that Mn bioaccumulation can occur in biofilters using filter packing media with much larger void spaces (25mm pebbles) than those typically used (sand) at water treatment sites. The removal efficiency of manganese over the first 70 hours of operation was 75.22%. After that removal efficiency slowly increased to 95% in the next 80 hours of the operation. There after equilibrium concentration of manganese has been reached and no further improvement in removal efficiency was observed.
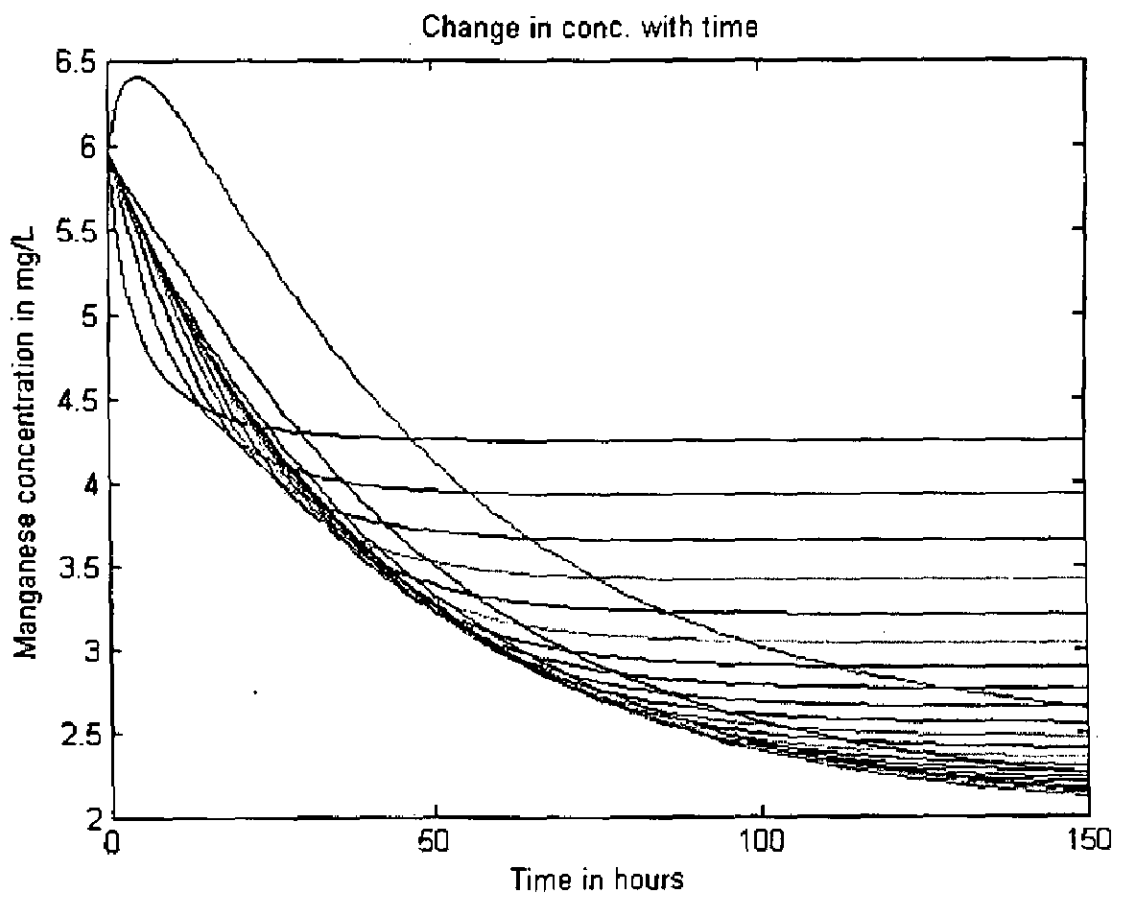
Fig 5.7 Manganese concentration with operational time
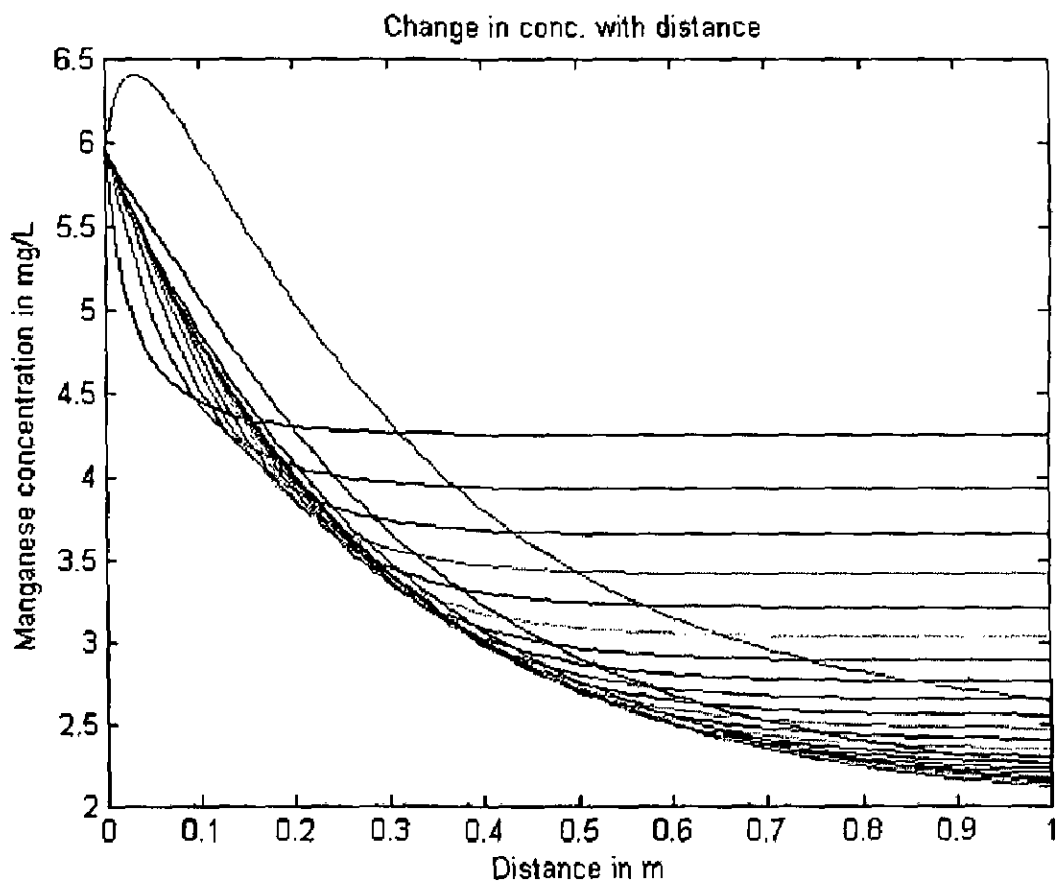biofilter at different lengths.

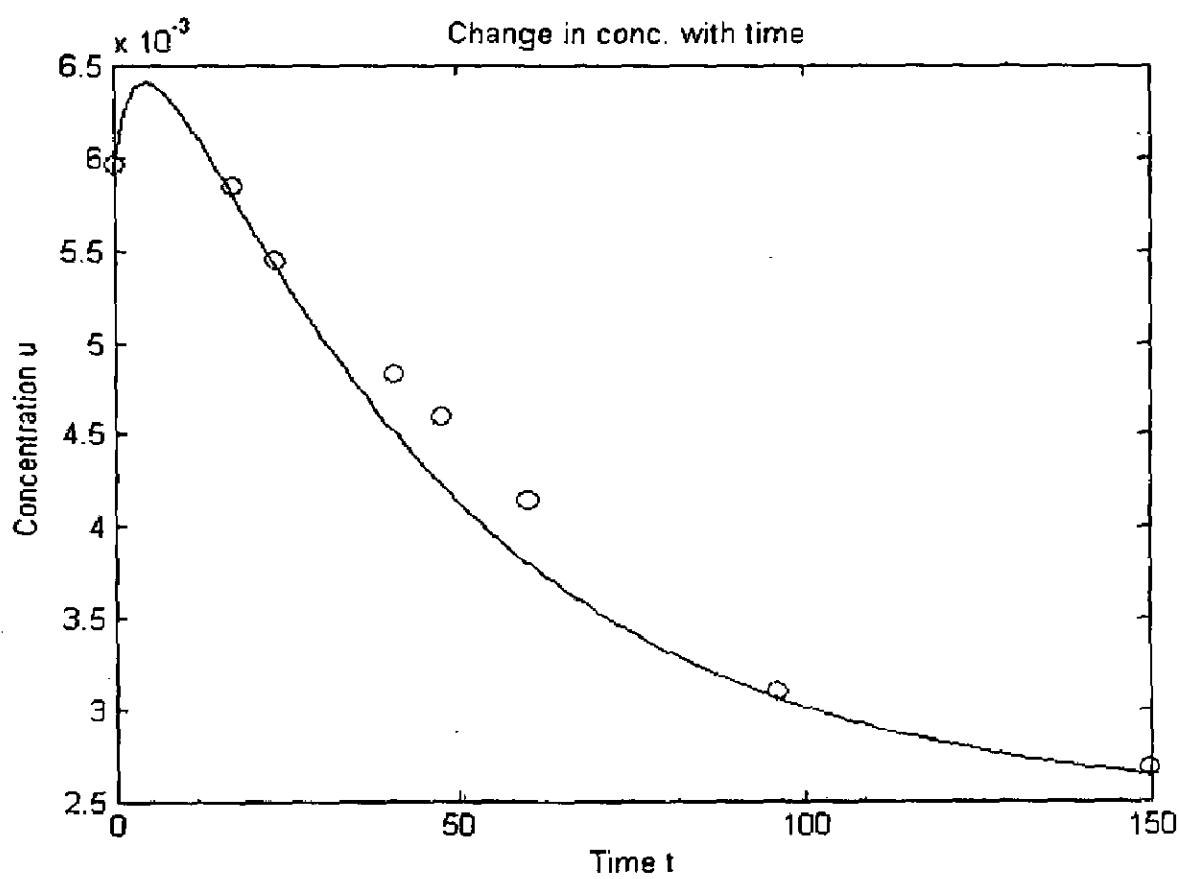**Fig 5.8 Manganese concentration along the length of the biofilter at different times.**

Fig 5.9 Validation plot for Manganese concentration in the biofilter.

5.5 EFFECT OF VELOCITY ON BIOACCUMULATION RATE

Simulations at various velocities have been carried out to see the effect of flow rate on the process. Bioaccumulation rate has been calculated for each run and plotted against velocity. Based on the simulations best flow rates to carry out the removal process in the biofilter for Cobalt, Lead and Manganese are determined. Figures 5.10, 5.11 and 5.12 show the plots (velocity vs. Bioaccumulation rate) for cobalt, lead and manganese respectively. From these plots, we shall be able to deduce the best flow rate that will give good results for the removal of heavy metals from wastewater using biofilter.
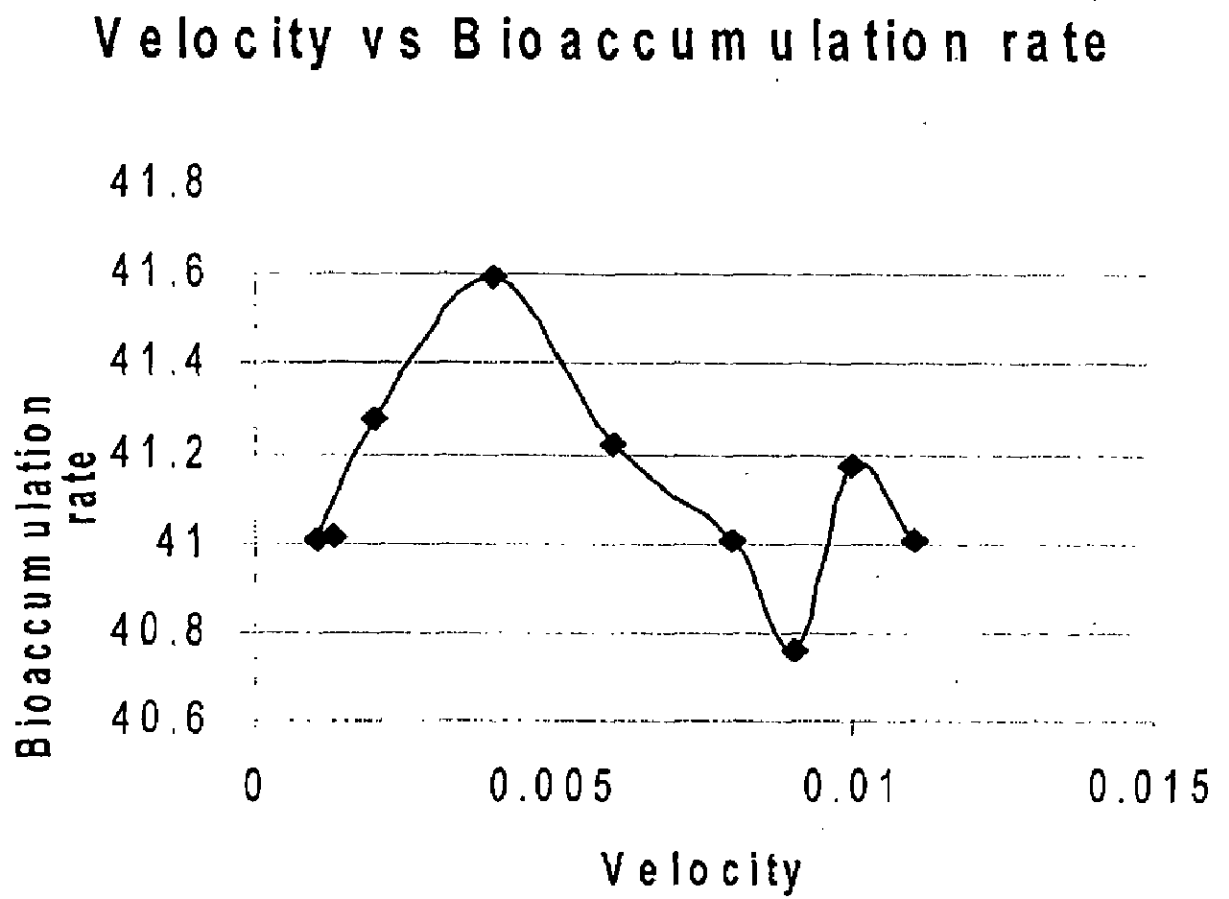
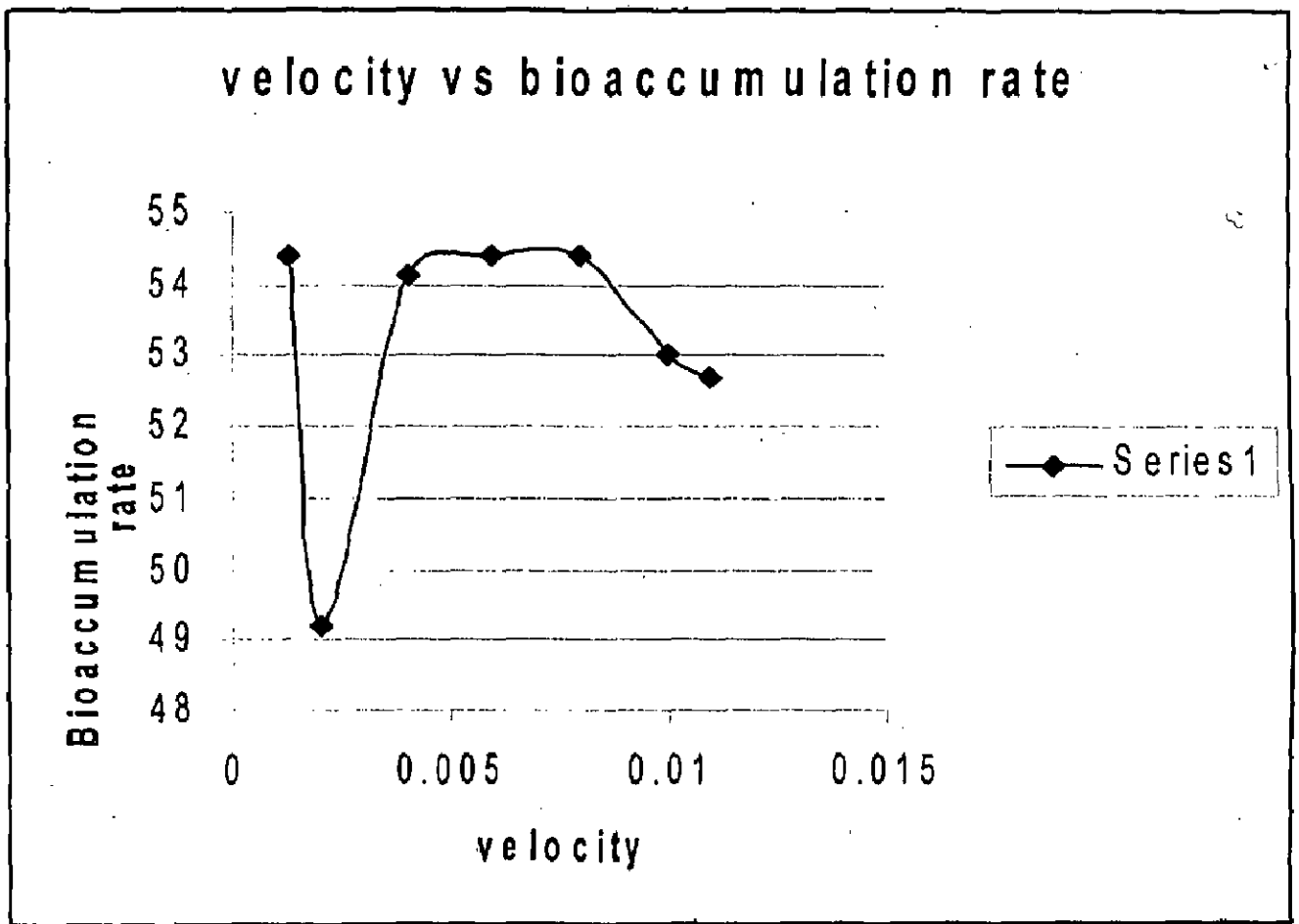**Fig 5.10 Velocity vs. Bioaccumulation rate curve for Cobalt removal**

Fig 5.11 Velocity vs. Bioaccumulation rate curve for Lead removal

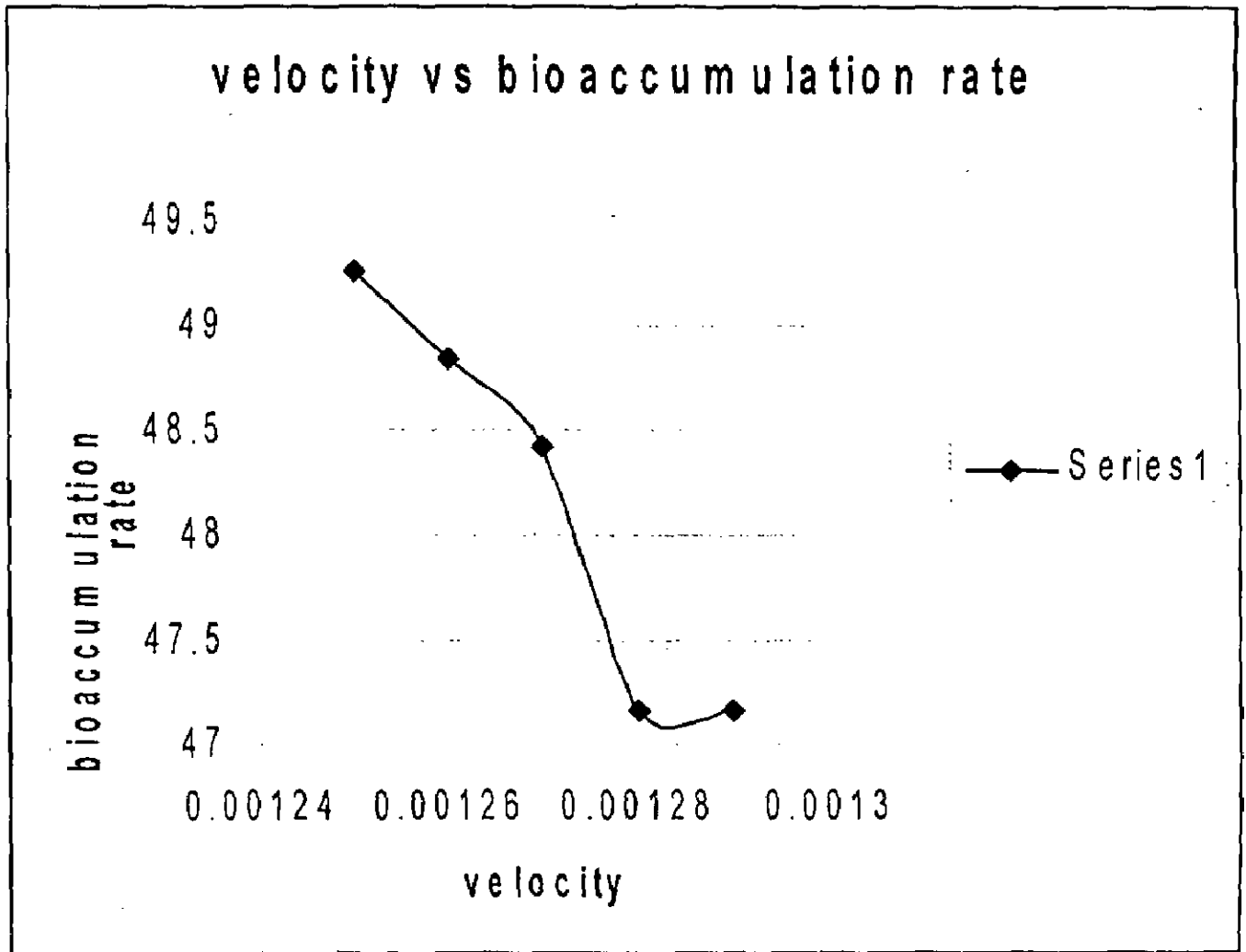**velocity vs bioaccumulation rate**

Fig 5.12 Velocity vs. Bioaccumulation rate curve for Lead removal

5.6   CONCLUDING REMARKS

In this chapter all results regarding the study of different parameters are represented graphically. The performance study of biofilter for removal of heavy metals has been verified with three metals i.e. with cobalt, lead and manganese. Also to validate the model simulation parameters available from literature are used to solve model equations. It was also found that all the results were in good agreement with the results obtained in literature. In general the results presented in this chapter show that biofilter can be used for the removal of heavy metals from wastewater at low concentrations i.e. below 7mg/L.

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The removal of heavy metals in a biofilter was simulated using a simple mathematical model, which was developed under appropriate assumptions. The changes in the concentration of heavy metals along the length of the biofilter with time were shown. The effect of change in flow rates was explained. Good agreement was found between the calculated values and experimental ones. Based on the simulation results, biofilter can be used for the purpose of removal of heavy metals from wastewater, where heavy metal's concentration is low i.e. below 7 mg/L.

6.2 RECOMMENDATIONS FOR FUTURE WORK

No work has been carried out on removal of multiple metals using biofilter. So we recommend to carry out experiments related to the biosorption kinetics for simultaneous removal of metals from wastewater using biofilter.

The results obtained in the laboratory are sometimes quiet different from those obtained at commercial level. It is, therefore, recommended that the model developed here should be tested with the data from commercial biofilters. It will enhance the applicability of the model.

REFERENCES

Byung-Ran Lim, Hong-Ying Hu· Xia Huang, Koichi Fujie, (2002).

"Effect of seawater on treatment performance and microbial population in a biofilter treating coke-oven wastewater".

Process Biochemistry, 37, pp. 943–948.

C. Hu, K. Acuna-Askar and A.J. Englande, Jr, (2004).

" Bioremediation of methyl tertiary-butyl ether (MTBE) by an innovative biofilter".

Water Science and Technology, 49, 1, pp. 87-94.

C.K. Hope, T.R. Bott (2004).

"Laboratory modeling of manganese biofiltration using biofilms of Leptothrix discophora"

Water Research, 38, pp. 1853 -1861.

C.M. Falkentoft, P. Harremoës, H. Mosbæk and P. Wilderer, (2000).

"Combined denitrification and phosphorus removal in a biofilter".

Water Science and Technology, 41, 4–5, pp. 493–501.

Durgananda Singh Chaudhary, Saravanamuthu Vigneswaran, Huu-Hao ngo, Wang Geun Shim and Hee Moon, (2003).

"Biofilter in water and wastewater treatment".

Korean Journal of Chemical Engineering, 20, 6, pp. 1054-1065.

H. Horn and U. Telgmann (2000).

"Simulation of tertiary denitrification with methanol in an upflow biofilter"

Water Science and Technology, 41, 4–5, pp. 185-190.

Hozalski, R.M., and Bouwer, E., (2001a).

"*Non-steady state sinulation of BOM Removal in Drinking Water Biofilters: Model Development*".

Water Research, 35, 1, pp. 198 – 210.

Hozalski, R.M., and Bouwer, E., (2001b).

"*Non-steady state sinulation of BOM Removal in Drinking Water Biofilters: Application and Full- scale validation*".

Water Research, 35, 1, pp. 211 - 223.

James D. Bryers (2000)

Biofilms II: Process analysis and applications.

Wiley Series in Ecological and Applied Microbiology

Ralph Mitchell, Series Editor.

Jennifer (2002).

"*Electrowinning: New Technology for Removing Heavy Metals from Wastewater*".

Caswell: Electroplating in miniature, pp. 1 -14.

Jerome Jacobe, Jean-Marc Le Lann, Herve Pinguad, Bernard Capdeville (1997).

"*A generalized approach for dynamic modeling and siulatation of biofilters; Application to wastewater denitrification*".

Chemical Engineering Journal, 65, pp. 133-143.

J. Jacob, H. Pingaud, J.M. Le Lann, S. Bourrel, J.P. Babary, B. Capdeville, (1996).

"*Dynamic simulation of biofilters*"

Simulation Practice and Theory, 4, pp. 335-348.

John H. Duffus, (2001).

·*"Heavy Metals"- A Meaningless Term ".*

Chemistry International, 23, 6, pp. 793 – 807.

J. Park, S. Takizawa, H. Katayama and S. Ohgaki (2002).

"Biofilter pretreatment for the control of microfiltration membrane fouling"

Water Science and Technology: Water Supply, 2, 2, pp 193–199.

L. Travieso , A. Pellón , F. Ben'ıtez, E. Sánchez , R. Borja d,, N. O'Farrill, P. Weiland (2002)

"BIOALGA reactor: preliminary studies for heavy metals removal"

Biochemical Engineering Journal, 12, pp. 87–91

Marc Valls, Victor de Lorenzo (2002).

"Review: Exploiting the genetic and biochemical capacities of bacteria for the remediation of heavy metal pollution".
FEMS Microbiology Reviews, 26, pp. 327-338

Metcalf & Eddy (2003).
Wastewater Engineering: Treatment and Reuse, Fourth edition.
Tata McGraw Hill Edition

Nicholas R. Axtell, Steven P.K. Sternberg, Kathryn Claussen (2003)

"Lead and nickel removal using Microspora and Lemna minor"

Bioresource Technology 89, pp. 41–48.

Paul – Gene Chung, Dong – Heui Kwak and Youngchul Kim (1996).

"Application of a Simple Empirical Fixed – Film Model to the Fluidized Biofilter

97

process"

Water Science and Technology, 34, 4 -5, pp. 427 – 433.

P.Viotti, B. Eramo, M. R. Boni, A. Carucci, M. Leccese, S. Sbaffoni (2002).

"Development and calibration of mathematical model for the simulation of the biofiltration process"

Advances in Environmental Research, 7, pp. 11 – 33.

Sudha Sagar Ratnala, (2004).

"Studies on Batch activated sludge with Biosorption for industrial wastewater",

Dept. of chemical engg. IITR, (M.Tech Dissertation).

Sushil kumar Srivastava, (1991).

"Removal of heavy metal (lead) from wastewater",

Dept. of Chemical engg., U.O.R., (M.E. Dissertation).

X. Le Tallec, A. Vidal and D. Thornberg (1999).

"Upflow Biological filter: Modeling and Simulation of Filtration"

Water Science and Technology, 39, 4, pp. 79 – 84.