PERFORMANCE OF HYDROGEN -DRIVEN DENITRIFYING MEMBRANE BIOFILM REACTOR (MBfR)

By Dominika Celmer

A Thesis Submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements
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Performance of Hydrogen - Driven Denitrifying Membrane Biofilm Reactor (MBfR)

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

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To My Grandpa Stanislaw Maciejewski

ABSTRACT

The goal of this research was to develop and evaluate the method of controlling structure of biofilm and performance of membrane biofilm reactor (MBfR) for hydrogen driven denitrification. The particular nitrate contaminated streams treated in this study include synthetic ground water- used in initial studies on feasibility of MBfRs, and tertiary wastewater obtained from North End Water Pollution Control Centre (NEWPCC) - used for actual evaluation of analyzed methods. The controlling methods were based on hydrogen limitation, application of shear force caused by mixing and nitrogen sparging and introducing ultrasound treatment into operating mode of MBfR.

It was found that starving conditions (restricted hydrogen supply) limit biofilm development and allow maintaining stable denitrification rates (0.59+/- 0.04 gNO_3-N $d^{-1}m^{-2}$). Despite the availability of excess nitrates no significant growth of microorganisms was observed within the biofilm. Larger fluctuations were observed in measured total solids (TS) concentration within biofilm. Increase in TS and overall biofilm density was caused either by precipitation of the buffer substances or an attachment of solids present in the incoming wastewater, which appeared to be the main weakness of this method.

The application of shear force was found to minimize biofilm thickness, and increase biofilm density. The density of the biofilm was still significantly lower then the values obtained in system operated with hydrogen limitation and overall changes in biofilm structure allow obtaining higher removal rates (up to 0.93 +/- 0.14 g N $(d^* m^2)^{-1}$ for 300 μm thick biofilm). Hydrodynamic shear force was a reliable and efficient tool for controlling biofilm structure and MBfR performance.

The test with ultrasound treatment allowed to increase the denitrification rate up to 1.17+/- 0.11 gNO_3-N m^{-2} d^{-1} for the highest tested dosage. The benefit of high removal rates was minimized by the negative impact of ultrasound on biofilm viability observed for high ultrasound dosages. Moderate dosages were recommended as they were found to increase bacteria viability within a biofilm, probably due to removal of excess dead cells. It was found that ultrasound has no significant impact of volatile solids concentration but in high dosages it can cause decrease in protein content and destabilize the biofilm matrix. Similarly, application of ultrasounds seemed to diminish the hydrogen utilization rate (HUE) as values of 15 – 46% were observed while application of mixing and nitrogen sparging used as a shear force resulted in much higher observed HUE (40% to 100%).

The analysis of the cost of introducing of MBfR for tertiary treatment showed that it can be good alternative for heterotrophic denitrification. Hydrogen - driven denitrification within MBfR with full denitrification controlled by high level of mixing would be recommended as it combines good and stable effluent quality with low net present value (NPV) of the created system.

The analysis showed that different operating modes affect the protein, carbohydrates and EPS content within biofilm, as well as biofilm stability and MBfR performance.

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MBfR – membrane biofilm reactor
NO_3 – N – nitrogen in form of nitrates
SDR – specific denitrification rate
COD – chemical oxygen demand
TCOD – total chemical oxygen demand
SCOD– soluble chemical oxygen demand
DO – dissolved oxygen
TSS – total suspended solids
VSS – volatile suspended solids
HUE – hydrogen utilization efficiency
r – biofilm thickness
R- fibre radius
V – biofilm volume
l - fiber length
TS – total solids concentration within a biofilm (total solids density)
VS – volatile solids concentration within a biofilm (volatile solids density)
VS/TS – ratio of volatile to total solids within a biofilm
EPS – extracellular polymeric substances
p – total proteins content
c- total carbohydrates content
μ_{max} – maximum specific growth rate
S – concentration of limiting substrate in the solution
X – biomass concentration
Y – maximum yield coefficient
K_s – half velocity constant
k- max rate of substrate utilization per mass unit
m_s- substrate required for maintenance
μ - viscosity of the fluid
τ_w shear stress due to viscous effects
P - normal stresses due to the pressure
F – acting force, centripetal force
A- surface area of the submerged body
m – body mass
v – velocity
r – radius
ω – angular velocity

CHAPTER 1: INTRODUCTION[1]

1.1 THE FUTURE OF NUTRIENT REMOVAL

In 1914, Ardern and Lockett introduced activated sludge technology into wastewater treatment facilities (Ardern and Lockett, 1914) and provided a means for larger cities to begin protection of water supplies and prevention of waterbourne illness. Research completed since the inception of these process developed a more complete understanding to permit greater control of the bacterial processes involved and hence development of nutrient modifications to activated sludge. Today, the emerging approach of limiting both immision and emission of nutrients stands as the State-of-the Art for wastewater treatment technologies and offers promise of better protection of receiving waters while both causing dispute and opening new avenues of research (Murthy and Oleszkiewicz, 2007).

The new emerging limit of technology (LOT) based regulations combining emission and immision standards, aim at developing sustainable practices of water reclamation and protecting receiving waters from negative changes after effluent discharge. Implementation of LOT creates new areas of research for both nitrogen and phosphorus removal. These include refinement of existing nitrogen and phosphorus removal processes to achieve greater removals and development of new polishing nitrogen and phosphorus removal processes to facilitate very low nitrogen and phosphorus effluent

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[1] Part of this chapter were accepted for publication in International Journal of Environment and Waste Management (2007)
Formation of autotrophic nitrogen-removing biofilms on porous and non-porous membranes
D.Celmer , J. –H. Hwang, N.Cicek, J. Oleszkiewicz

concentrations. Such an advanced wastewater treatment is defined as any process designed to produce an effluent of higher quality than normally achieved by secondary treatment processes or containing unit operations not normally found in secondary treatment (Sonune and Ghate, 2004). The increasing space needed for advanced treatment launched the search for alternatives which include biofilm reactors as one of the promising options. Biofilm reactors progressed in the second half of last century with the introduction of plastic media and with increased understanding of the process mechanism. The application of biofilm technology when used to its optimal potential can be applied as a treatment solution for the most stringent requirements.

1.2 PRESENT AND FUTURE OF NITRATE REMOVAL

Nitrate is one of the primary pollution of groundwater, which causes the eutrophication of natural environments and is known to have adverse effects on human health (Blue Baby Syndrom) and livestock health (lower milk production, reduced weight gain, stillborn calves). Due to the effect of nitrate on health the World Health Organization (WHO) set the limit for nitrate in drinking water at 10 mg NO_3-N l^{-1}, which magnifies the importance of nitrate removal from both wastewater and drinking water. There are several alternatives for nitrate removal including physical (ion exchange, electrodialysis, and reverse osmosis), chemical (reaction with aluminum and ferric) and biological (heterotrophic or autotrophic denitrification) methods. While, physical and chemical methods are mostly used for drinking water, biological denitrification is widely used for wastewater treatment.

1.3 POTENTIAL OF AUTOTROPHIC BIOLOGICAL DENITRIFICATION FOR TREATMENT OF LOW ORGANIC CARBON STREAMS

1.3.1 Heterotrophic vs. autotrophic biological denitrification

The biological denitrification process completes nitrogen removal from the stream by converting nitrate and nitrite to nitrogen gas. There are many genera of bacteria which are able to carry out this process. Most of the denitrifiers are heterotrophic bacteria from species such as *Achromobacter, Acinetobacter, Agrobacterium, Alcaligenes, Bacillus, Chromobacterium* (Lee et al., 2002). Heterotrophic denitrification involves biological oxidation of many organic substrates in wastewater using nitrate or nitrite as the electron acceptor. Electron donors generally come from one of three sources:

- Biodegradable, soluble COD in the influent stream (wastewater),
- Biodegradable, soluble COD produced during endogenous decay,
- Exogenous COD source such as methanol, ethanol, or acetate.

The stoichiometry of heterotrophic denitrification depends on the type of carbon source utilized [Metcalf & Eddy, ed. IV, 2003].

a) Biodegradable organic matter from wastewater:

$$C_{10}H_{19}O_3N + 10\ NO_3^- \longrightarrow 5N_2 + 10CO_2 + 3H_20 + NH_3 + 10OH^- \quad (1.1)$$

b) methanol:

$$5CH_3OH + 6\ NO_3^- \longrightarrow 3N_2 + 5CO_2 + 7H_20 + 6OH^- \quad (1.2)$$

c) acetate :

$$5CH_3COOH + 8\ NO_3^- \longrightarrow 4N_2 + 10CO_2 + 6H_20 + 8OH^- \quad (1.3)$$

An alternative option is autotrophic denitrification. The energy source for autotrophic denitrifiers comes from oxidation/reduction reactions with elements such as hydrogen or

sulphur as the electron donor. For that reason, autotrophic denitrification processes have been divided into hydrogen-based and sulphur–based reactions (H_2S, $S_2O_3^{2-}$, $S_4O_6^{2-}$, SO_3^{2-}, S). Substances present in the water or wastewater, such as CO_2 or HCO_3^- are the inorganic source of carbon for the bacteria.

The stoichiometry of the hydrogen and sulphur driven autotrophic denitrification process is as follows:

$$NO_3^{-2} + 2.86H_2 + H^+ + 0.15CO_2 \longrightarrow 0.03C_5H_7O_2N + 0.49N_2 + 3.14H_2O \qquad (1.4)$$

$$55S + 44CaCO_3 + 50NO_3^{-2} + 18H_2O + 3NH_4 \longrightarrow$$

$$4C_5H_7O_2N + 25N_2 + 55SO_4^{-2} + 44Ca^{+2} + 24HCO_3^- \qquad (1.5)$$

The strains of sulphur-based denitrifiers are *Thiobacillus denitrificans* and *Thiomicrospira denitrificans*, while hydrogen driven autotrophic denitrification is carried out by *Ochrobactrum anthropi, Pseudomonas strutzeri, Paracoccus denitrificans,* and *Paracoccus panthotrophus* (Liessen et al, 1992; Selenka and Dressler, 1990).

As a result of differences in carbon source, autotrophic and heterotrophic bacteria exhibit different kinetic parameters. Autotrophs use more of their energy on cell synthesis then heterotrophs, thus their yield of cell mass and growth rates are lower. The autotrophic vs. heterotrophic biomass yield is 0.24:0.6 or 0.24: 0.9 g $C_2H_5O_2N$ (g NO_3-N)$^{-1}$ removed (Metcalf and Eddy, 2004; Wisniewski et al, 2001; Vasiliadiou et. al., 2006). Process rates (denitrification) are also lower for autotrophic than heterotrophic bacteria. The comparison of the denitrification rates is presented in the Table 1.1.

The treatment of low organic carbon wastewaters is often plagued by inefficient nitrogen removal, due to inhibited heterotrophic denitrification process. Lack of organic electron donor is usually solved by adding expensive external organic carbon source (methanol,

ethanol). An excess of organic carbon in the effluent is a common by–product of such a treatment due to fluctuations in nitrate concentrations. Eliminating the need for organic carbon addition, preventing residual organic carbons in the effluent, low biomass yields, lower chemical cost, can be achieved by application of autotrophic denitrification where carbon dioxide is used as carbon source. Carbon dioxide is present in wastewater in various forms such as $H_2CO_3^-$ or HCO_3^- and hydrogen and sulphur have to be supplied to the wastewater stream.

Table 1.1 The comparison of the denitrification rates for hetero- and autotrophic, hydrogen driven denitrification

external source of electron donor	specific denitrification rate	literature
	[mg N/ g VSS* h]	
methanol	34	Hagman et al., 2008
methanol	3.2	Peng et al., 2007
methanol	3	Nyberg et al., 1996
ethanol	15	Hagman et al., 2008
ethanol	9.6	Peng et al., 2007
ethanol	10	Nyberg et al., 1996
acetic acid	4.5	Patel J. And Nakhla G., 2006
acetic acid	1-3	Kujawa K., 1999
acetic acid	6.2	Hagman et al., 2008
acetic acid	12	Peng et al., 2007
acetic acid	1.6	Pala A. And Bolukbas O., 2005
acetate+ ethanol	14-40	Hagman et al., 2008
butiric acid	3.2	Patel J. And Nakhla G., 2006
propionic acid	1.6	Patel J. And Nakhla G., 2006
glucose	1.2	Pala A. And Bolukbas O., 2005
MWW	1.2	Patel J. And Nakhla G., 2006
MWW	0.6-1	Kujawa K., 1999
primary effluent	1.2	Patel J. And Nakhla G., 2006
endogenous COD	0.2-0.6	Kujawa K., 1999
lactate	6.9	Sage et al., 2006
lactose	5.1	Sage et al., 2006
casein	3.7	Sage et al., 2006
whey protein	2.6	Sage et al., 2006
molasses	2.9-3.6	Quan Z.X. Et al., 2005
fatty acids from PS	0.46	Elefsiniotis P. et al., 2004
hydrogen	17-22	Rezania et al., 2005
hydrogen	9.16-15.41	Kurt et al., 1987
hydrogen	110	Vasilidiou et al., 2006
	[g N/ m^{-2} d^{-1}]	
methanol	0.24	Liessen et al., 1992
methanol	4	Mansell and Schroeder, 1992
hydrogen	2.7-3.5	Mansell and Schroeder, 2002
hydrogen	0.32	Kurt et al., 1987
hydrogen	0.79	Islam et al., 1993
hydrogen	2	Gantzer et al., 1995
hydrogen	1.39	Benedict et al., 1997
hydrogen	0.001	Lee and Ritman, 2000
hydrogen	2.2	Ergas and Reuss, 2001

MWW – municipal wastewater

PS – primary sludge

1.3.2 Hydrogen driven vs. sulphur driven denitrification

In sulphur-driven autotrophic denitrification, electrons come from sulphur particles used as packing media in the reactor. Limited pilot-scale experiments have proven that the process can give the best solution for medium level nitrate wastewater with low organic content. Application of elemental sulphur, however, was found to be inefficient. Powdered elemental sulphur, under normal circumstances, is insoluble and tends to conglomerate and float (Lampe and Zhang, 1996). Thiosulfate, as a soluble substance, is a much more efficient electron donor in the process of denitrification. Still, due to the creation of sulphates and hydrogen ions (eq. 1.5), sulphur driven autotrophic denitrification causes a significant decrease in pH, which can inhibit the denitrification at pH = 5.5 . In order to keep the pH in the proper range, buffering agents have to be added to the system. Dolomite, slaked lime, unslaked lime, limestone, marble stone and crushed oyster shells have been evaluated as the buffering substances (Sengupta et.al, 2007). Crushed oysters were found to be efficient buffer agents as they allowed to obtain higher denitrification rate, pH and alkalinity in effluent, higher alkalinity release and resulted in lower nitrite accumulation as well as lower turbidity in effluent (Sengupta et al, 2007).

Hydrogenotrophic denitrification offers two major advantages over sulphur driven denitrification and heterotrophic denitrification. First, it is practically impossible to have a residual of the supplemented donor, since H_2 evaporates to the atmosphere once the water (wastewater) is exposed to an open surface. Second, it does not leave any by–products which affect quality of the effluent.

1.3.3 Advantages of hydrogen driven denitrification

Hydrogen driven denitrification is an attractive option for removing nitrate from low organic carbon streams. As already mentioned is does not leave any residuals or by-products of the reaction, produces less biomass compared to heterotrophic denitrification and results in lower cost of supplied electron donor per unit of nitrate removed when compared to heterotrophic denitrification.

The analysis of the reactions of heterotrophic, methanol- driven (eq. 1.2) and hydrogenotrophic denitrification (eq.1.4) show that activation energy (defined as the energy that must be overcome in order for a chemical reaction to occur) of the latter one is lower. In case of hydrogen driven denitrification the activation energy equals – 72 kJ / e, while for methanol driven denitrification it is – 37 kJ/e (Ersever et al.,2007). The requirement for electron donor for hydrogenotrophic denitrification would be lower as well, as the number of molecules with the energy equal or greater than the activation energy will be lower.

The comparison of requirements for methanol and hydrogen in heterotrophic and autotrophic denitrification respectively shows that methanol requirement is equal to ~ 1.2 - 3 kg CH_3OH (kg NO_3-N)$^{-1}$ removed (Schlekovski and Mavinic, 1998; Brauer and Annachhatre, 2004) while H_2 requirement equals only to ~ 0.42 kg H_2 (kg NO_3-N)$^{-1}$ removed. Higher methanol consumption is affected not only by denitrification but also by dissolved oxygen (DO) which is usually carried from previous treatment zones and by non- ideal flow conditions which lead to downstream methanol leakage. Lower H_2 requirement and thus technical and economical viability of hydrogen – driven

denitrification depends on efficient hydrogen supply into the system. Detailed economical study is presented in Chapter 8.

1.3.4. Challenges of hydrogen driven denitrification - attempts at increased efficiency of hydrogen delivery

Low solubility of hydrogen gas in water and related issues with efficient delivery are important challenges. In initial tests Aragno and Schlegel (1992) and other researchers (Szekeres et al., 2001) described risks associated with the explosive nature of a mixture of hydrogen and oxygen. Thus efficient hydrogen utilization became the focus of reactor designs. A common way of supplying the necessary gases to the reactor is through the use of conventional diffusers. This can result in the delivery of excess hydrogen and creation of an explosive atmosphere (Terada et al., 2006; Kurt et al.,1987; McAdam and Judd, 2006). Other techniques of gas transfer, resulting in new reactor configurations were developed in order to overcome this disadvantage and improve the efficiency of autotrophic nitrogen removal. Attached growth (biofilm) reactors became the centre of attention of researchers working on removing nitrate by means of hydrogen driven denitrification.

1.3.4.1 Fixed film reactors and biofilm electrode reactors (BER)

Fixed film reactors (Kurt et al., 1987; Gross et al., 1988; Dries et al., 1988) were used for treatment of groundwater but relatively low removal rates of around 0.3 g NO_3-N $m^{-2}d^{-1}$ were obtained. Low saturation coefficient of hydrogen impeded gas diffusion from the surrounding bulk into the biofilm and decreased denitrification rates. The biofilm

electrode reactors (BER), which allowed for on-site production of hydrogen, were tested and rates similar to fixed film reactors were obtained (Prosnansky and Sakakibara, 2002; Kiss et al.,2000; Fleke et al., 1998). The main drawback of the BER was intensive precipitation of minerals within a reactor and consequent creation of crust on the membrane surface, which deteriorated systems efficiency, as well as high costs of used materials.

1.3.4.2. Membrane biofilm reactors

The development of membrane technology allowed using membranes diffusers in reactors carrying out hydrogenotrophic denitrification (Stephenson et al, 2000; McAdam and Judd, 2006). In the membrane biofilm reactor (MBfR), hydrogen is supplied by the membrane, which also acts as the surface for biofilm growth. Hydrogen diffuses from the inside of the biofilm, while nitrate and CO_2 diffuses from the surrounding bulk liquid. The biofilm creates conditions favourable for growth of autotrophic microorganisms, which are associated with long solids retention time and require a protective environment. Figure 1.1 presents the schematic of the fibre supplying hydrogen covered with biofilm.

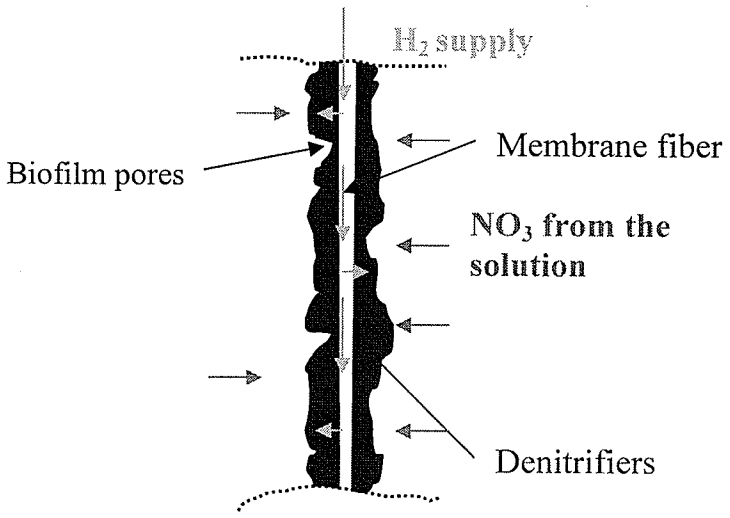


Figure 1.1 Schematic drawing of fiber covered with biofilm population (not to scale)

New developments in the manufacturing of novel membranes from a variety of polymeric materials have expanded their use in process involving microbial communities (Rittman, 2006). A general overview of membrane systems used for nitrogen removal is summarized in Table 1.2 (MacAdam and Judd, 2006).

Table 1.2 Classification of membrane bioreactors used for nitrate removal

Reactor configuration	Principle of operation	Membrane type	Removed pollutant	Type of process	Main challenge
1. extractive membrane reactors	biological growth treatment with suspended and fixed biofilm	microporous membrane	nitrate/ nitrite	*heterotrophic denitrification* [Mansell and Schroeder,1999; Ergas and Rheinh eimer,2004] *autotrophic denitrification* [Mansell and Schroeder, 2002]	organic carbon pollution of effluent; hydrogen accumulation
2.ion exchange membrane reactor	biological treatment with suspended and fixed biofilm	dense ion-exchange membrane	nitrate/ nitrite	heterotrophic denitrification [Fonseca et al., 2000,Velizarov, 2000/2001]	complexity of operation and high cost of membranes; fouling of exchange efficiency
3.gas transfer membrane	**biological treatment with fixed biofilm**	gas permeable membranes	**nitrate/ nitrite /ammonia**	*autotrophic denitrification nitrification [Lee and Rittman, 2003]*	Sloughed biomass and soluble microbial products contamination, biofilm accumulation and diffusion limitation
4. pressure driven membrane biofilm reactor	biological treatment with suspended and filter cake	microporous membrane	nitrate/ nitrite	*heterotrophic denitrification* [Barrieros et al, 1998; Urbain et al.,1996; Chang et al.1993; Delanghe et al.,1994] *autotrophic denitrification* [Kimura et al.2002]	Membrane fouling, organic carbon breakthrough in effluent

1.4 POTENTIAL OF MBfR FOR AUTOTROPHIC DENITRIFICATION OF LOW ORGANIC CARBON WASTEWATER

The MBfR are a promising option as they:

(1) eliminate the need for organic carbon addition,

(2) prevent passing of residual organic carbon to the effluent,

(3) result in low biomass yields,

(4) lower chemical cost,

(5) provide efficient utilization of many process gases (such as H_2),

(6) provide extensive surface for biofilm attachment,

(7) allow for extended solids retention times and high biomass concentration,

(8) enable higher volumetric removal rates,

(9) require a relatively small reactor footprint,

(10) utilize electron donor (hydrogen) which is harmless to human health and does not require any steps to remove its excess or derivatives.

The attractiveness of the MBfR is also associated with the fact that biofilm formation is inevitable as mineral solids and microorganisms tend to accumulate and create a biofilm at the interface with a solid surface i.e. membrane (Lewandowski and Beyenal, 2005; Lee and Rittmann, 2003). Biofilm formation is a very complex process and its final shape is the result of a variety of attachment, growth, and detachment processes. The detailed information on the biofilm formation process is discussed further (1.5.1.1. Biofilm formation).

The complexity of biofilm formation (Beyenal and Lewandowski, 2005) leads to non-uniform layers covering the gas permeable membrane surface. Substrate limitation

caused either by leakage of gas from uncovered fibers or restrained nutrients diffusion due to excess biofilm accumulation (Terada et al., 2006; Lee and Rittmann, 2000; Semmens et al., 2003; Satoh et al., 2004) are the main challenges of this conceptually very promising method. As hydrogen is supplied from the lumen side of the membrane and nitrates diffuse from the surrounding solution, hydrogen and nitrates are never present at the same location at their maximum concentration (Essila et al., 2000). This may lead to dual diffusive limitations, which was described by Terada et al. (2006) who observed the deterioration of denitrification efficiency as biofilm structure changed. The growth of the microbial population and high rate of extracellular polymeric substances accumulation lead to changes in biofilm structure. Mineral precipitation may have a long–term negative impact on the process as inert inorganic solids accumulate inside the biofilm and at the interface with the membrane (Lee and Rittmann, 2003). The diffusional resistance of the biofilm increases with increasing biofilm thickness and density. The biofilm consists mainly of water (usually over 90%) thus due to high solubility of nitrate in water (880 mg l^{-1} at 20° C), the nitrate concentration in the biomedium (biofilm) can be high enough to penetrate the whole, even relatively thick biofilms (Emanuaelsson and Livingston, 2003). The solubility of hydrogen gas is however lower (1.82 mg l^{-1} at 20° C) and thus effective utilization of hydrogen gas within thick biofilm might be deteriorated. Also water condensation inside the pores of the membrane reduces mass transfer efficiency. This can lead to the reduction of nitrogen removal rates and may cause biofilm sloughing from the membrane surface deteriorating effluent quality. Thus the main drawback of the MBfR is that, with a build up of the

biofilm, the flux reduction across the biofilm is observed. Therefore, in case of a thicker biofilm, only a fraction of the biofilm remains active.

The most important challenges associated with application of MBfR concern efficient gas and substrates supply and are as follows (Rezania et al., 2006):

(1) Gas diffusers are fragile and any damage to the structural integrity of the membrane causes gas release and its inefficient supply,

(2) Porous membranes are subject to condensation of water vapour in the pores,

(3) Fluctuations in biofilm structure cause variations in MBfR performance,

(4) Formation of insoluble metal salts (with calcium, magnesium) increases biofilms diffusional resistance. From an engineering point of view uncontrolled biofilm development in MBfR is an unwanted process as it leads to the deterioration of systems performance.

The steps to monitor and control biofilm parameters such as its thickness, density, EPS content and biofilm composition have to be taken into consideration while employing a MBfR.

The feasibility of controlling the denitrification rate and the biofilm parameters in MBfR needs to be tested. Efficient gas supply, establishing stable and high removal rates, reducing start–up time, elucidating the competition between bacterial consortia, and understanding the impact of operational parameters have become the main objectives of researchers working with MBfRs (Terada et al., 2006).

1.5. IMPACT OF ATTACHED GROWTH CONDITIONS ON MBfR PERFORMANCE

Controlling biofilm structure (i.e. its thickness, density and composition) is an important factor affecting MBfR efficiency. Biofilm formation is a multi-step process to which physicochemical (diffusion force, gravity force, thermodynamic forces, opposite charge attraction, hydrophobicity, etc.) and biological (production of extracellular polymer, growth of cellular clusters, metabolic changes, etc.) forces make significant contributions. The stable three dimensional structure of the biofilm is ultimately a function of the interactive strength between aggregates and hydrodynamic shear force (Liu and Tay, 2002).

1.5.1 The biofilm life cycle, structure and composition

1.5.1.1 Biofilm formation

The process of biofilm formation is very complex and depends on many factors. Some of the most important factors are presented in the following Table 1.3 (Wimpenny et al. 2000).

Table 1.3 Factors influencing the biofilm formation

Phenotypic factors
1. specific genotype of the microorganisms
2. expression of genes encoding surface properties
3. expression of signaling system
4. formation of EPS
5. organism growth dynamics:
a/ specific growth rates
b/ lag periods
c/ affinity for substrates
d/ yield coefficient
6. Expression of genetic factors not directly connected to biofilm formation (mobility, chemotaxis)
Physico- chemical factors
1. phase interface (combination of solid, liquid and gaseous
2. substratum composition and roughness
3. substrate composition
4. substrate concentration gradient
5. temp, pH, pressure DO
Stochastic processes
1. initial colonization (attachment , detachment)
2. random changes in biotic and abiotic factors
Determistic phenomena
1. specific interactions between microorganisms (cooperation, competition, neutralism, predation)
Mechanical processes
1. shear due to laminar or turbulent flow conditions, abrasion
Import - export
1. adition or removal of biotic and abiotic components to a biofilm system (sand, clay , minerals)
2. sloughing of biomass
3. release of the individual cells
Temporal changes
1. diurnal and annual changes in environment (biotic and abiotic)

The final shape of the film is the result of all mentioned factors. The process of biofilm formation can be divided into attachment, growth, and detachment processes. Main driving forces in the attachment phenomenon are adhesion and microbial growth. In the initial stages, the biofilm is created as the result of both depositions of cells and particles

from the bulk and microorganisms cell reproduction (Oliveira et al. 2001; Buscher et al., 1990). Initiation of attachment occurs thanks to conditioning films, which are created on the membrane surface. The surface is coated with adsorbed organic molecules as soon as it is placed into a natural aqueous environment. It is often easier for the bacteria to attach to a surface when it is covered with this film. The properties of the film depend on the nature of the surface material and on the kind of molecules present in the aqueous environment. Different bacteria have different nutrient needs as well as different cell surface characteristics and are therefore attracted to different kinds of conditioning films. Most biofilms can also accumulate many inorganic particles because of the adhesive properties of extracellular polymeric substances (EPS) (Allison and Sutherland, 1987; Azerado and Oliveira, 2000). In many occasions these particles can contribute more to the overall deposit mass than the active biomass. For older biofilms, detachment also affects the biofilm composition and characteristics. A variety of factors have been suggested to be important in biofilm detachment: shear and normal forces exerted by the fluid, matrix degrading enzymes, microbially generated gas bubbles, nutrient starvation and microbial growth status, availability of multivalent cations, and quorum sensing (coordinating certain behaviors based on the local density of the bacterial population) (Rittman, 1982, Speitel and Digiano, 1987, Picioreanu et al. 2001, Peyton and Characklis, 1993).

Main detachment processes are related to microbial growth and decay characteristics. These are shedding of daughter cells (the microorganisms tend to multiply and find new environment) and detachment as the result of limiting nutrient levels. The latter one is connected with decay processes present in each microbial population under starving

conditions. The decay process depends on the microorganism concentration – the higher the biomass density the faster the decay process. However it is different for each microorganism population as each exhibits different decay coefficients. Sloughing, which is defined as rapid and massive removal of biofilm particles, occurs when biofilm thickness creates mass transfer limited conditions and results in intensive decay.

In case of membrane biofilms, physical forces contribute to detachment processes as well. There is constant removal of small portions of biofilm, so called erosion or sheering in reactors with constant, intensive mixing. Detachment occurs due to collision of particles from the treated liquid with the biofilm. This process is called abrasion.

A pictorial description of the process of biofilm creation is shown in the Figure 1.2

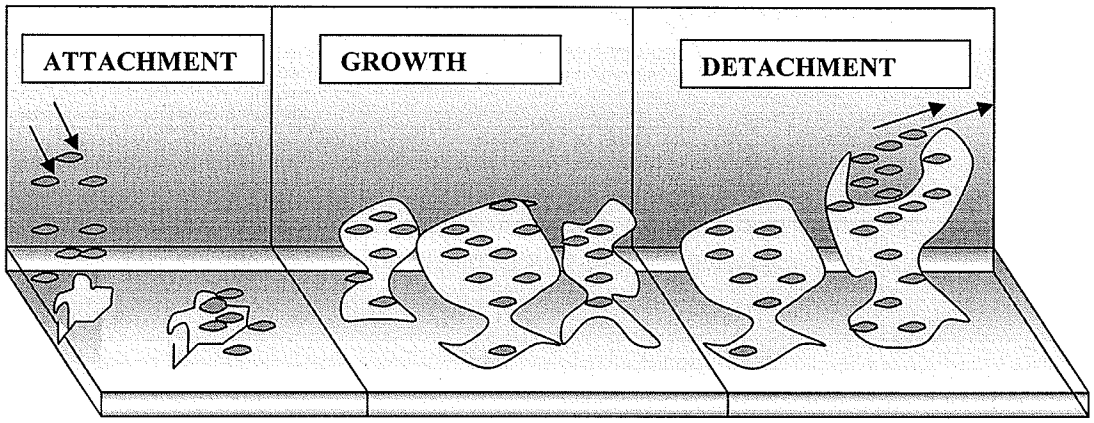


Figure 1.2 Biofilm formation (adapted from Centre for Biofilm Engineering at MSU-Bozeman, 2003)

1.5.1.2 Biofilm composition and structure

The biofilm consists of a biomass layer and a stagnant liquid film. In most cases, the biofilm biomass layer consists not only of living microorganisms but also contains

considerable amount of abiotic organic and inorganic material. In general, biofilms contain (Flemming H., Szewzyk U. , Griebe T., 2000):

(1) Water (>90%)

(2) EPS – extracellular polymeric substances (up to 90% of organic matter)

(3) Biomass cells

(4) Entrapped particles and precipitates

(5) Sorbed ions and polar and nonpolar organic molecules

The biofilm structure consists of solids, which create cell clusters, voids and channels as showed on the Figure 1.3. Biofilm layers are not simply planar but are in fact very complex, nonuniform structures with uneven protrusions and have vertical and horizontal pores through which liquid flows (Metcalf & Eddy, 2003).

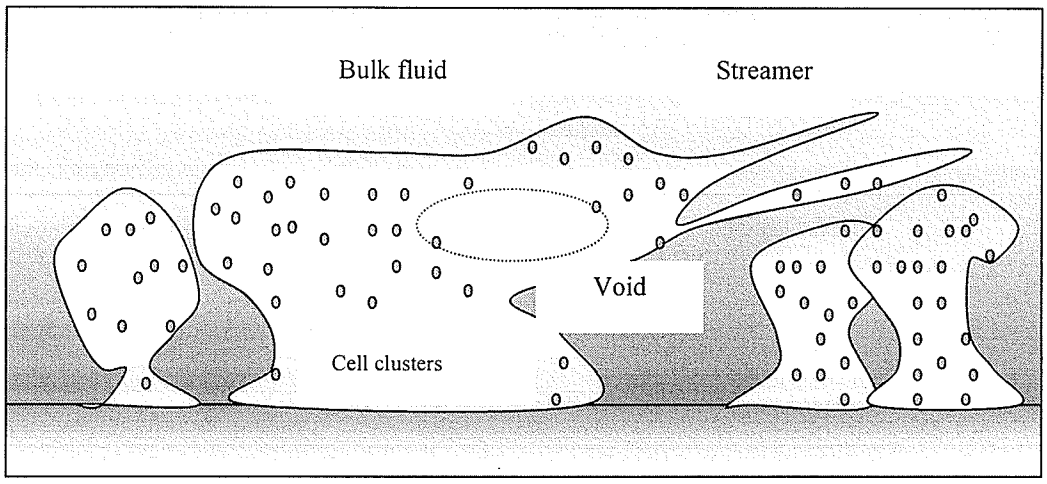


Figure 1.3 Biofilm structure (adapted from Centre for Biofilm Engineering at MSU-Bozeman, 1996).

The ratio of living and dead cells, content of EPS (extracellular polymeric substances) and minerals particles and porosity of the biofilm strongly affect obtained removal rates thus they have to be monitored during systems operation.

1.5.1.3 Biofilm thickness, porosity and density

The thickness of the biofilm as well as its porosity and density are important structural parameters, which are strongly connected to each other. The biofilm thickness can range from 10μm to 10mm and is affected by the many parameters such as density, bacteria species, biofilm age, operating conditions (Metcalf&Eddy, 2003). The biofilm porosity is inversely proportional to biofilm density, as the higher number of pores the more space for liquid flow.

Biofilm density can be expressed in terms of total solids concentration (TS) or volatile solids concentration (VS). The microorganism content in the whole biofilm volume is, in many cases really small. However it is crucial to detect their presence and estimate their number as microorganisms play crucial role in deposit formation (Flemming H., Szewzyk U., Griebe T., 2000). The biomass concentration, measured as volatile solids, usually range from 40 – 100g l^{-1} (Metcalf&Eddy, 2003), however different values like 10 – 160 g l^{-1} can also be found in the literature (Fan et all, 1989).

Density of the biofilm is an important factor in defining its properties and performance. Biofilm density depends on many factors such as biofilm thickness, bacterial species, bulk composition, hydrodynamics of the system, and biofilm age.

The relationship between biofilm thickness and density is unclear. Some researchers claim that biofilm density decreases as thickness increases (Fan et all, 1998; Livingston

and Santos, 1995). Trulear and Characklis (1981) observed a completely opposite tendency, which meant that density increased together with biofilm thickness. Finally some data indicate that density of the deposit increases with thickness, but only to some point, after which it starts to drop (Hoehn and Ray, 1973).

Another important factor is the bacteria species composition present in the film. Different species produce different extracellular polymer substances which further affect adhesion processes, biofilm thickness and density.

Hydrodynamics conditions in the membrane reactor also affect biofilm thickness and density. Increased velocity and flow leads to higher shear stress and decreased biofilm thickness due to decrease in boundary layer thickness (stagnant liquid film). Biofilms created in high shear stress conditions are more compact (less porous) and can be characterized by higher density (Livingston and Santos, 1995).

The structure of the biofilm changes with its age. Usually older biofilms have higher density and are less porous.

As the final biofilm structure depends on many varying parameters and at the same time affects the biofilm removal efficiency the detailed analysis of all biofilm structure parameters is necessary for controlling the biofilm parameters and membrane biofilm reactors performance.

1.5.1.4 Microbial composition

In most of cases both environmental and medical biofilms are heterogeneous. A basic structural microbial unit of a biofilm is called a microcolony, which is a dense aggregate of microorganisms. Microcolonies are composed of multiply species, which enables

efficient cycling of various nutrients (carbon, nitrogen, sulfur). While fluid flows through biofilm channels allowing nutrient, gases and sometimes antimicrobial reagent transport, the proximity of cells in a microcolony provides the optimum conditions for microbial growth. These conditions create nutrient gradients that allow for the exchange of genes and enables quorum sensing.

The different bacterial species are the main microbial component of biofilms. The presence of each species depends on the growth environment. There can be heterotrophic, autotrophic, gram- negative and gram – positive bacteria creating microcolonies. Due to microbial heterogeneity, both competition and coexistance of different species occurs in biofilms. Competition is also called invasion of new species which better acclimate to the in- situ environmental conditions and can be characterized by their higher growth rates (James et al. 1995). Nevertheless, different species are also able to coexist in a stable community. This cooperation is often the result of balance between different growth rates and the ability to attach to each other (Stewart et al., 1997).

Besides bacteria, free living protozoa are often part of biofilms existing in aerobic conditions. Well concentrated cell clusters are perfect predation environment for protozoa (Murga et al., 2001). Researchers proved that several bacterial pathogens also associate and grow in biofilms however they are not able to compete with indigenous organisms (Camper et al., 1998).

1.5.2 Attached growth conditions create protective environment

Utilizing a biofilm population for autotrophic denitrification might diminish the influence of negative parameters. As the structure of the biofilm creates a protective environment,

the impact of operational parameters such as DO, pH, antimicrobial factors (such as antibiotics or other antimicrobial agents) on denitrification can be less significant in a MBfR. This might be important for hydrogenotrophic denitrification within MBfR as autotrophic denitrification is carried out by sensitive to adverse conditions, facultative microorganism, which can also use oxygen or other compounds as the electron acceptor. Nitrate or nitrite removed during the process serve as the alternative electron acceptor, thus the presence of excess oxygen inhibits denitrification efficiency. Also their resistance to varying pH conditions is not clear yet. Lee and Rittman (2003) suggest that the optimum pH range is 7.7 – 8.6, while Shin and Sang (2005) state that the highest efficiency of denitrification occur for pH lower than 7.6.

Increased antimicrobial resistance is a phenomena commonly observed in microbial biofilms. Several mechanisms have been suggested to account for the recalcitrant nature of the biofilm when challenged with a negative agent. Failure of the agent to penetrate the full depth of the biofilm, nutrient limitation and slow growth, and the existence of the protected phenotype within the biofilm are some of them (Hunt, 2004).

The penetration of antimicrobial agents is reduced as the result of the reactions within the biofilm. The negative agents are neutralized by reactions with the extracellular polymeric substances (EPS) matrix creating the biofilm. Nutrient limitation within biofilms has been well documented. This combined with the fact that slow-growing bacteria have been shown to be less susceptible to antimicrobial agents, provides the mechanism for biofilm resistance. The idea of a "persistent cell" or protected phenotype implies that a small percentage of the bacteria within the biofilm (<1%) exist in a highly protected state. The

protected subpopulation is sheltered from antimicrobial agents and is capable of recultivating the biofilm (Hunt, 2004).

1.6. RESEARCH GOALS

The feasibility of applying membrane reactors and biofilm systems in wastewater treatment has been demonstrated in previous research studies (Masuda et al., 1983; Brindle et al., 1998; Timberlake et al., 1998; Ahmed et al., 1992; Pankhania et al., 1994). Several researchers carried out tests involving autotrophic (hydrogen-driven) nitrate removal from water and wastewater in membrane biofilm reactors (MBfR) (Shin et al., 2005; Terada et al., 2006; Satoh et al., 2004; Rittman et al., 2005). However, the applicability of the MBfR for tertiary wastewater treatment strongly depends on the stability of operation. Previous experiments showed that denitrification efficiency in MBfR can be repressed by limitation in hydrogen or nitrate diffusion in the thick biofilm (Beyenal and Lewandowski, 2000).

Controlling biofilm structure (i.e. its thickness, density and composition) is therefore a key factor affecting MBfR efficiency.

The objective of this research is to evaluate different strategies aiming at stabilizing and improving the performance of MBfR for autotrophic denitrification of low organic carbon stream. Specific objectives are:

1.6.1 Evaluating the applicability of non – porous membrane diffusers in MBfR for treatment of low organic carbon content streams.

1.6.2. Assessing the impact of main operational parameters (pH and DO) on MBfR performance.

1.6.3 Evaluating feasibility of substrate limitation as the method of controlling and stabilizing biofilm structure and MBfR performance.

1.6.4. Evaluating feasibility of pH control as the method of diminishing the effect of precipitation and controlling biofilm structure and MBfR performance.

1.6.5 Evaluating feasibility of applying shear force as the method of controlling and stabilizing biofilm structure and MBfR performance.

1.6.6 Evaluating feasibility of applying ultrasound treatment as the method of controlling and stabilizing biofilm structure and MBfR performance.

CHAPTER 2: MATERIALS AND METHODS

2.1 EXPERIMENTAL DESIGN OF THE MBfR SYSTEM

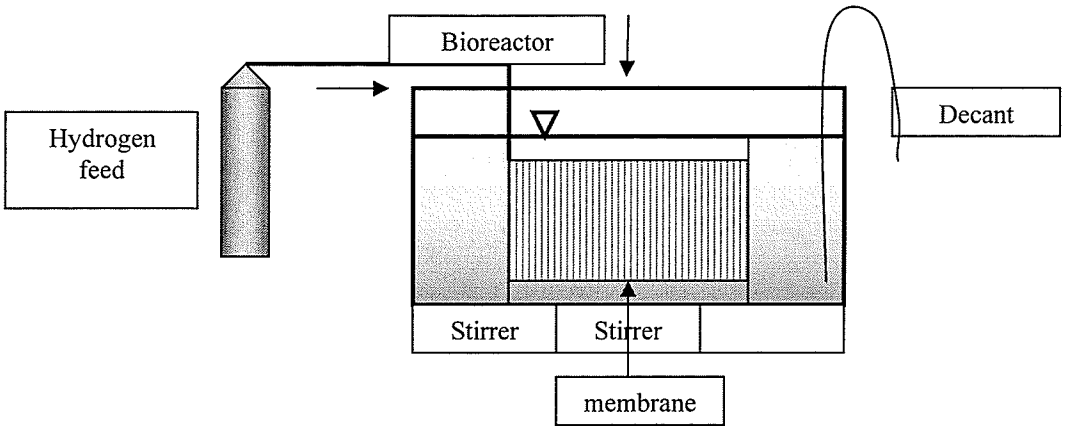
The schematic of the membrane biofilm reactor (MBfR) is presented on Figure 2.1. Two types of the new membrane modules provided by GE Water & Process Technologies ZENON Membrane Solutions were used during the experiments. The flat sheet module and fiber module, both composed of diffusive, hollow fibers made from polypropylene suitable for efficient hydrogen gas diffusion. In case of flat sheet module the hollow fibers were embedded into the woven sheet. The detailed description of the used membranes is presented in following chapters as the dimensions of supplied membranes varied slightly. The configuration of the reactors used during experiments with flat sheet module and fiber module are presented on the Figure 2.1(a) and 2.1(b) respectively.

The flat sheet module system was composed of a 70 L glass tank with a working volume of 50L. It was operated in batch system mode with pump #1 responsible for filling the reactor and natural decanting of its total volume at the end of the cycle.

The fiber module system was composed of plexiglass tank of a working volume of 3 L. It was operated in continuous flow mode in order to simulate wastewater treatment plant conditions.

Detailed descriptions of reactor operation during each of the experiments including cycle time, hydraulic retention time, gas supply, mixing conditions are presented in the specific research chapters.

(a)



Filling – ~ 40 min ***Operation*** – 3 days ***Decant*** – ~ 20 min
Hydrogen flow - constant

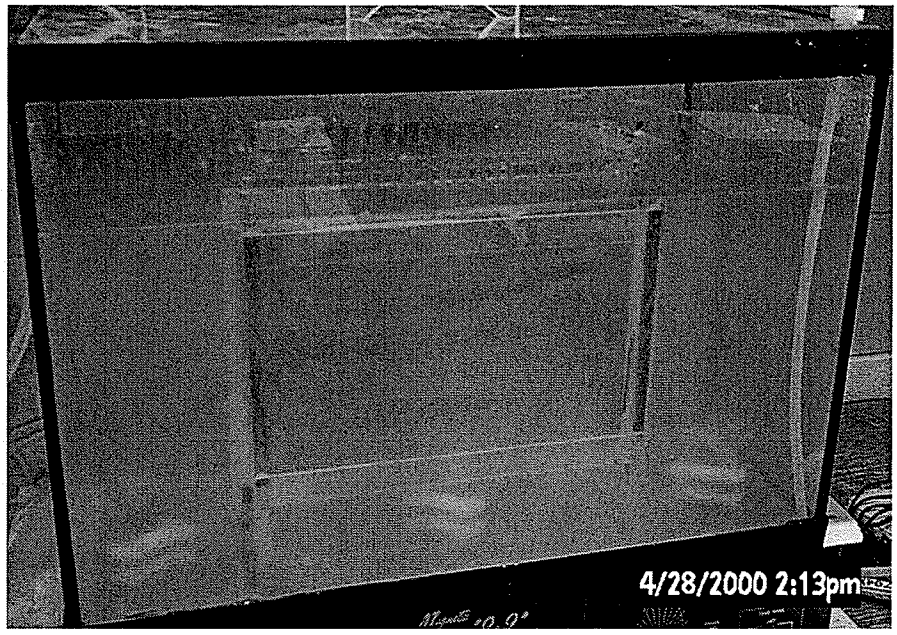
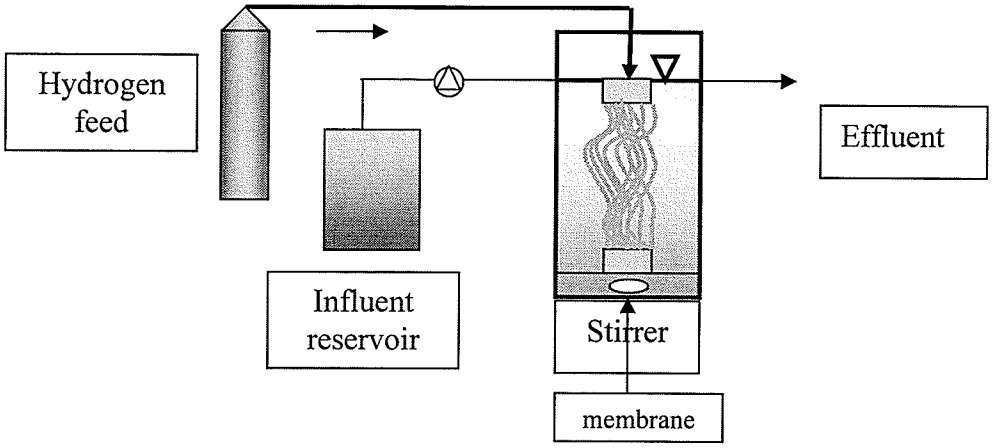


Figure 2.1 (a) Schematic and picture of hollow fiber hydrogen diffusing MBR with fibers embedded in woven sheet to create flat sheet structure.

(b)



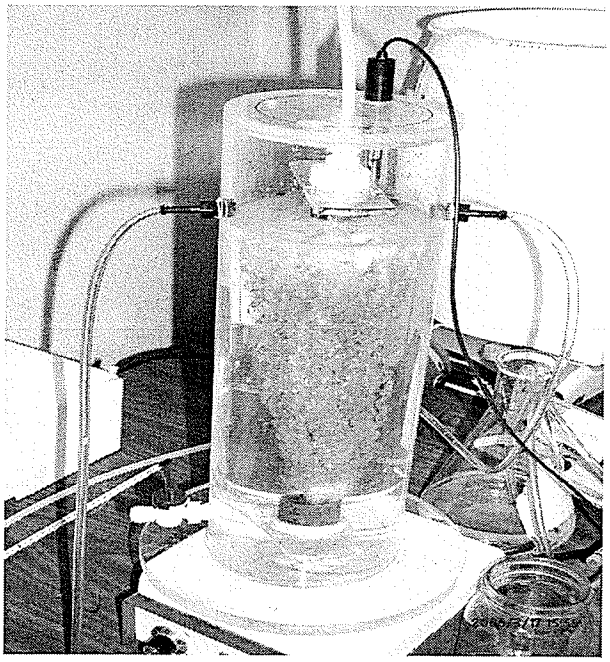


Figure 2.1 (b) Schematic of hollow-fibre hydrogen diffusing MBR

2.2 WATER & WASTEWATER CHARACTERISTICS

Detailed characteristics of water and wastewater are described in the following chapters. The synthetic ground water (for detailed descriptions please refer to Chapter 3, point 3.2.1) was used in initial phase of tests. Synthetic wastewater (for detailed description please refer to Chapter 4, point 4.2.1) was used in intermediate phase of experiment. Municipal wastewater obtained from final effluent of North End Water Pollution Control Centre was used as the medium during final experiments (for detailed description please refer to Chapter 4, 5, 6 (points 4.2.1, 5.2.1, 6.2.1)

2.3 ANALYTICAL METHODS

2.3.1 Physical analysis

- **Total suspended solids and volatile suspended solids**

Mixed liquor suspended solids (TSS and VSS) were analyzed following Standard Methods 2540D and 2540E (APHA, 1998). Basing description of the method is presented below:

1. Filter each sample through a filtration crucible of known mass, with glass microfibre filter.
2. Place crucibles in oven at 105°C for approx. 24 hours. Cool crucibles in desiccator and measure total mass once cool.
3. Place crucibles in furnace at 550°C for approx. 2 hours. Cool crucibles in desiccator and measure total mass once cool.

- **Temperature**

The temperature was determined using HACH Sension 378 DOmeter. All the determined values were based on results from duplicates.

2.3.2 Chemical analysis

- **pH**

pH was determined using ORION 91-05 pH electrodes. All the determined values were based on results from duplicates.

- **dissolved oxygen**

The dissolved oxygen (DO) concentration was determined using HACH Sension 378 DOmeter. All the determined values were based on results from duplicates.

- **extracellular polymeric substances content (EPS)**

The characterization of the extracellular polymeric substances (EPS) bound within the biofilm were carried out by measuring the dry weight content (at 105 °C) of extracted EPS. EPS concentration during tests with hydrogen limitation was determined using the method of sequencing thermal treatment, centrifugation and acetone and ethanol precipitation (Morgan et all, 1990).

During rest of the tests, the EPS were extracted in three steps: (1) addition of DOWEX MARATHON C cation exchange resin and extraction (2 h at 20°C), (2) centrifugation (10000 rpm, 10 min) and (3) acetone and ethanol precipitation (24 h at 4°C) (Comte et

al., 2004). As the method was applied for biofilm analysis some modification were introduced. The detailed description of the method is presented below.

Measurement of Extracellular Polymeric Substances Using Cation-Exchange Resin Extraction

Procedure:

4. Obtain biomass samples of known volume
    a. For biofilm: scrape small sample of biomass (approx. 0.05 ml) from biofilm, measure volume through displacement of water, and dilute to 10 ml in a small beaker.
5. Add appropriate mass of cation-exchange resin to each beaker based on estimated volatile suspended solids of sample.

    Required CER is calculated basing on the theoretical demand of 75 g CER gVS^{-1}. (Rudd et al., 1983; and Frolund et al., 1996).
6. Mix each sample using magnetic stirrer for 2 hours for extraction.
7. Pour each sample into micro centrifuge cups, and centrifuge samples for 10 minutes.
8. Remove supernatant from micro centrifuge cups and place into glass vials corresponding to each sample.
9. Add 10 ml of ethanol to each glass vial and refrigerate for approx. 24 hours.
10. Filter each sample through a filtration crucible, of known mass, with glass microfibre filter.
11. Place crucibles in oven at 105°C for approx. 24 hours. Cool crucibles in desiccator and measure total mass once cool.

12. Place crucibles in furnace at 550°C for approx. 2 hours. Cool crucibles in desiccator and measure total mass once cool.

- **soluble nitrate and nitrite in influent and effluent**

NO_3 and NO_2 concentrations were determined colorimetrically using TECHNOCON autoanalyzer (results from Chapter 3,4,5) and Lachat QuickChem 8500 (results from Chapter 6) following Standard Methods 4500-NO3-F (APHA, 1998).

- **total and soluble oxygen demand (TCOD and SCOD)**

Total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD) of samples were measured using the Hach Digestion Vials (Digestion Solution for COD 0-150ppm range, Cat. 21258-15) and Hach Spectrophotomer DR/2500 (Hach, USA) before and after filtration through 0.45 μm membrane filters following Method 8000. All the determined values were based on results from duplicates.

- **total carbohydrates**

Carbohydrates content within a biofilm was determined using the anthrone assay with glucose standards (Viles and Silverman, 1949).

Anthrone assay protocol for the determination of Carbohydrates

1. Prepare a 0.1% (w/v) of Anthrone reagent in 95% H_2SO_4
    a. 0.1g per 100ml
    b. The solution is stable for assays after 4hours
    c. The solution can be stored for up to 7 days

2. Samples must be diluted such that their concentrations are within 0-400 ug ml^{-1}
3. Prepare standards of cellulose for each days experiment (0,10,20,50,100,150,200 $\mu g\ l^{-1}$):
4. 2.0ml of Anthrone reagent was added to previously prepared sample of the biofilm
5. Incubate samples at room temperature for 30min to allow the hydrolysis of cellulose
6. Samples were then placed in a boiling water bath for 5 minutes and cooled to room temperature for 30-45min
7. Absorbance can be read at 595nm or 620nm. The protocol for the KCjunior plate reader agitates the samples and then reads at 620 nm.

- **total proteins**

Proteins content within the biofilm was determined using modified Bradford method with BSA standards described in detail below (Bradford, 1976):

Protein assay (Modified Bradford method) protocol for the determination of proteins

1. Centrifuge 1 ml culture at 14000 rpm for 10 min
2. Separate supernatant from the pellet
3. Re-suspend the pellet in 0.9% NaCl solution to wash it
4. Discard the supernatant after centrifuge
5. Re-suspend the pellet in 1 ml (same amount as culture taken) of 0.2N NaOH solution
6. Boil in water bath for 10 min

7. Centrifuge for 5 min
8. Use the supernatant for protein assay
    - Prepare BSA protein standards from (10 ug ml^{-1} to 100 ug ml^{-1}) on 0.2N NaOH

Bradford solution preparation:

In a 1000 ml glass container take 300 ml of milliQ water and dissolve the followings,

- Coomassie brilliant blue: 25 mg
- 85% sulfuric acid: 50 lm
- 95% ethanol: 25 ml
- Add water to bring the final volume up to 500 ml.

Keep the prepared stock solution in 4°C and in a brown bottle.

Table 2.1 Compositions and concentrations of standards. Total volume of each standard solution will be 1000 µl

No.	Stock + 0.2N NaOH composition	Vol (µl)	BSA (mg/ml)
1	20% + 80%	200 +800	0.2
2	10% + 90%	100 + 900	0.1
3	05% + 95%	50 + 950	0.05
4	03% + 97%	30 + 970	0.03
5	02% + 98%	20+ 980	0.02
6	01% + 99%	10 + 990	0.01

- Filter the Bradford reagent (stored at 4°c)
- Add 200 microliter of Bradford reagent to each well
- Add 20 microliter of sample (supernatant) or standards in each well
- Add 20 microliter of NaOH to the blank wells
- Wait 5 min for color development
- Measure the absorbance at 595 nm. The signal should be stable for 60 min.

2.3.3 Biological analysis

➢ **Microscopic observation - biofilm structure investigation**

Biofilm samples were collected from the membrane surface for analysis of thickness, density, composition and EPS content. For this purpose, the membrane module was removed from the reactor for 15 mins and placed in vertical position to allow excess water to drain. The biomass was removed manually, with a plastic spatula from the fibres of known length and number and put into a 5ml plastic syringe, partially filled with deionized water (Ganczarczyk and Zahid, 1994).

➢ **Biofilm thickness**

Biofilm thickness (r) was calculated basing on the liquid volume displaced by the biomass and the area scraped from the module according to equation (2.1) (Zahid and Ganczarczyk, 1994)

$$r = \sqrt{(V/l \bullet \pi)} - R \qquad (2.1)$$

Where: r - biofilm thickness;

R- fibre radius;

V – Biofilm volume;

l - Fiber length.

- **Biofilm density**

Biofilm volumetric density was obtained by determining total and volatile solids of the sample with known volume (Ganczarczyk and Zahid, 1994).

Total solids density (g TS l^{-1}) was determined by measuring the total solids within the biofilm in order to determine the organic (bacteria cells, extracellular polymeric substances, adsorbed organic compounds) and inorganic (precipitated minerals, solids such as sand clay etc.) content of the film.

Volatile solids density (g VS l^{-1}) was determined by measuring the volatile solids within the biofilm in order to determine the organic (bacteria cells, extracellular polymeric substances, adsorbed organic compounds) content of the film. As volatile solids are a portion of the total solids, volatile solids density is a fraction of total solids density.

- **Biofilm porosity**

Samples of the biofilm for porosity (ratio of voids surface to total cross- section surface) determination were cut out together with the membrane module and embedded according to procedure suggested by the embedding kit supplier, Canemco Inc (JB- 4^{TM} Embedding Kit, Canemco Inc.). The samples were first fixed with neutral buffer, and then dehydrated, in a series of ascending concentrations of ethanol in distilled water (60%, 70%, 80%, 95%, for 20 minutes each). Infiltration process lasted more then advised 24

hours (36 hours), as the size of the embedded biofilm samples was relatively large (~0.3 cm^2). Finally the samples were placed in embedding resin (JB- 4^{TM} Embedding Kit, Canemco Inc.). The embedded samples were then cut into slices with glass knife on a microtome. Series of parallel sections with 2 microns thickness were made so to cover all depth of the biofilm. The morphology and spatial distribution of microorganisms in the biofilm were amplified by staining with toluene blue and methylene blue. Obtained slices were studied with the Nikon Eclipse E400 light microscope and Image - Pro Plus software for image analysis.

- **Bacteria viability**

The viability of cells was determined with LIVE/DEAD BacLight Bacterial Viability Kit (L7012) through quantitative assays using a RF-1501 SHIMADZU Spectorofluorophotomer (P/N 206-62901) with PC-1501 Personal Fluorescence Software. The tests were carried out according to procedure suggested by kit provider (Molecular Probes Invitrogen detection technologies).

Preparing standards:

1. Grow 30 ml of *E.coli* to the late log phase in nutrient broth.
2. Concentrate 25 ml of the bacterial suspension by centrifugation at 10 000 x g for 10 minutes.
3. Remove the supernatant and resuspend the pellet in 2 ml of 0.85 % NaCl buffer.
4. Add 1 ml of the suspension into 30 -40 centrifugal tubes containing either 20 ml of 0.85 % NaCl (live bacteria) or 20 ml of 70% isopropyl alcohol (dead bacteria).

5. Incubate both samples at room temperature for 1 hour, mixing thoroughly every 15 minutes.
6. Pellet both samples by centrifugation at 10 000 x g for 10 minutes.
7. Resuspend the pellets in 0.85 NaCl buffer.
8. Determine the optical density at the 670 nm (OD_{670}) of 3 ml aliquot of bacterial suspension in acrylic absorption cuvettes.

Preparing samples:

1. Place sample of the biofilm in the NaCl buffer and vortex for 15 – 20 min in order to deaglomerate the bacteria clusters.
2. Determine the optical density at the 670 nm (OD_{670}) of 3 ml aliquot of bacterial suspension in acrylic absorption cuvettes.

Staining bacteria:

1. Adjust the *E.coli* suspension (live and dead) and tested samples to $1x10^8$ bacteria/ml (~ 0.03 OD_{670}).
2. Mix five different proportions of *E.coli* bacterial suspensions in the 1 cm^3 acrylic cuvettes (Table 2.2). The total volume of each of the five samples will be 3 ml.

Table 2.2 Volumes of live- and dead- cells suspensions to mix to obtain standards

Ratio of Live:Dead Cells	ml Live cell suspension	ml Dead cell suspension
0:100	0.0	3.0
10:90	0.3	2.7
50:50	1.5	1.5
90:10	2.7	0.3
100:0	3.0	0.0

3. Prepare the 3 ml samples of the tested bacterial suspensions.

4. Prepare a combined reagent mixture in the centrifuge tubes by adding equal volume of SYTO 9 stain (component A) and propidium iodide (component B).
5. Add 9 µl of combined reagent mixture to each of the samples and mix thoroughly by pipetting up and down several times.
6. Incubate at room temperature in the dark for 15 minutes.
7. Measure the fluorescence emission spectrum (excitation: 470 µm, emission: 490-700 µm)of each of the sample (F_{cell}) in the fluorescence spectrophotometer
8. Calculate the ratio of the integrated intensity of the portion of each spectrum between 510- 540 µm (em1, green) to that between 620 -650 µm (em2, red) of each bacterial suspension.

$$R_{G/R} = F_{cell,em1} / F_{cell,em2} \qquad (2.2)$$

9. Plot the ratio of integrated green fluorescence to integrated red fluorescence ($R_{G/R}$) versus the percentage of the live bacteria in *E.coli* suspension.
10. Obtain viability of tested samples based on the plotted graph.

➢ **Visual biofilm and membrane structure investigation**

The structure of the membrane fibers were analyzed with Cambridge Stereoscan 120 Scanning Electron Microscope with black scattered electron detector, energy dispersive X-ray detector and digital image store facility.

CHAPTER 3: MEMBRANE BIOFILM REACTOR FOR HYDROGEN-DRIVEN DENITRIFICATION[2]

3.1 INTRODUCTION

Requirements concerning water and wastewater treatment plant effluents are becoming stricter. Nitrate – nitrogen and nitrite – nitrogen concentrations allowed for potable water are now equal to 10 mg NO_3-Nl^{-1} and 1 mg NO_2-N l^{-1} (Health Canada, US EPA), respectively. Requirements for wastewater are also very severe as usually permissible total nitrogen concentrations are around 10mg Nl^{-1} and, in some occasions, even as low as 3 mg N l^{-1}. Conventional methods of treatment in many cases are unable to assure proper effluent quality and new techniques are being developed. One such development has been in the area of autotrophic denitrification within membrane biofilm reactor which is a variation of an already well known heterotrophic denitrification.

In limited past research studies, biofilm processes for autohydrogenotrophic denitrification showed the ability to reduce nitrate concentration to levels below 0.1 mgN l^{-1} (Dries et al., 1988; Gros et al., 1988; Kurt et al., 1987). However, denitrification rates for this autotrophic process have been found lower than that for heterotrophic denitrification. Koenig and Liu (2004) found it to be in range of 0.14-0.19 g NO_3-N gVSS $^{-1}day^{-1}$. Other, more recent studies state that they can be in the range of 0.38-0.74 g NO_3-N gVSS $^{-1}day^{-1}$ (Rezania and Oleszkiewicz , 2004). This promising method has a number of advantages mentioned in chapter 1, point 1.4. The higher resistance of biofilm

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[2] Parts of this chapter were published in proceedings of 57th Annual conference of WCWWA, Saskatoon 2005
Membrane biofilm reactor for hydrogen driven denitrification
D.Celmer, J.Oleszkiewicz, N.Cicek

population to adverse conditions is one of the possible advantages of the membrane biofilm reactor.

Utilizing a biofilm population for autotrophic denitrification might diminish the negative influence of relatively high dissolved oxygen concentration which can be present in influent streams. Because denitrification is carried out by facultative microorganisms, the optimum dissolved oxygen concentration is low (below 0.2 mg/l) [Metcalf & Eddy, ed. IV, 2004]. The sessile bacterial populations are mostly heterogeneous colonies. A physiological corollary of the structural heterogeneity of the biofilms is that the substrate concentrations (like dissolved oxygen) vary from location to location in the biofilm. The biofilm is composed of dense aggregates of microorganisms embedded in gelatinous extracellular polymers and dissolved oxygen concentration inside of the biofilm clusters are lower than in the bulk water and biofilm voids (Lewandowski and Beyenal, 2005). Some researches proved that 60 μm thick biofilm creates two different layers: aerobic and anoxic (Satoh et al., 2003). Biofilm matrix might also provide an environment which protects from adverse pH range conditions and thus allows for stable and efficient performance of the systems.

A proper biofilm thickness and density provides a protective environment against changing conditions in the treated stream. Shearing stress caused by mixing and flow conditions is commonly present in water and wastewater treatment systems. Higher hydrodynamic shear force should minimize biofilm thickness and created stronger biofilm. Under weak shear force biofilm usually becomes porous and weaker in structure (Liu and Tay, 2002). At the same time there is an evident relationship between hydrodynamic conditions and substrate flux in the biofilm. Diffusivity of the substrate is

proportional to shearing force. Therefore shearing stress has a dual effect on mass transfer in biofilms. High turbulence facilitates substrate diffusion into biofilm but also increases biofilm density and reduces the diffusivity of substrate in the biofilm (Liu and Tay, 2002). As shear force changes the biofilm structure and diffusivity of the substrate changes too. It can also alter the protective environment created within the biofilm matrix.

3.1.1. Objectives

This study aimed to investigate autotrophic denitrification of synthetic groundwater within a biofilm growing on a hydrogen-introducing non – porous membrane. The evaluation of the process was carried out by analyzing denitrification rates as biofilm parameters such as density and thickness were changing. The impact of operational parameters such as dissolved oxygen concentration and shearing stress on the denitrification process were analyzed. As autotrophic denitrification occurred in the attached bacterial population, biofilm appearance, thickness, density and porosity were also evaluated.

3.2 MATERIALS AND METHODS

3.2.1 Reactor Operation (non porous membrane)

The experimental set-up involved a 70 l, laboratory-scale batch biofilm reactor (Figure 2.1(a)). The reactor was filled with 50 l of synthetic groundwater and was operated at 3 days reaction time (RT) throughout testing. The initial nitrate concentration was constant at 10 mg Nl^{-1} ($NaNO_3$). Composition of the synthetic ground water assured availability of

necessary inorganic carbon ($NaHCO_3$) and nutrients (Ca, Mg, Fe). Increased buffer concentrations were added to synthetic wastewater in order to provide phosphate necessary by microorganisms and prevent the system from significant pH increase due to denitrification. The detailed description of the groundwater composition is presented in Table 3.1.

Table 3.1 Synthetic ground water composition

Compound	Chemical formula	Concentration [mg/l]
Dipotassium hydrogen phosphate	K_2HPO_4	1100
Potassium dihydrogen phosphate	KH_2PO_4	900
Sodium bicarbonate	$NaHCO_3$	80
Calcium chloride (dihyrate)	$CaCl_2*2H_2O$	30
Magnesium sulphate (heptahydrate)	$MgSO_4*7H_2O$	20.5
Ferrous sulphate (heptahydrate)	$FeSO_4*7H_2O$	7.5
Sodium nitrate	$NaNO_3$	52

The bioreactor was seeded with a population of autotrophic denitrifiers at the first day of operation. The biomass was obtained from suspended growth membrane bioreactor carrying out hydrogenotrophic denitrification. The initial volatile suspended solids (VSS) concentration was 0.23 g l^{-1}. Hydrogen necessary for denitrification was delivered through a submerged membrane module, which was configured as flat sheet with hollow fiber diffusing hydrogen MBR embedded in woven sheet. The detailed description of the membrane is presented in Table 3.2. Three stirrers were placed under the reactor in order to improve mass transfer conditions. These stirrers were used to evaluate the impact of mixing on reactor performance. The experiment lasted 145 days and was initially divided into two parts: acclimation period, during which a biofilm was established and steady

state was achieved, and main operation period, when direct analysis of denitrification was carried out.

The pH during the experiment remained in the range of 6.93 – 7.80. No pH control was implemented, except for providing buffer solution in the feed. The average pH was 7.35. Temperature during the experiment was 26°C +/-4°C.

Table 3.2 Description of the gas diffusing membrane

Characteristic Property	Value
	Fiber module configurated as flat sheet
Manufacturer	Zenon Environmental Inc. GE Water & Process
Membrane material	polypropylene fibers embedded in woven sheet
Outer Diameter (OD) of fibers	50.9 μm
Inner Diameter (ID) of fibers	29.7 μm
Membrane surface area	0.14 m^2

3.2.2 Analytical Methods

Samples for NO_3^-, NO_2^- and TCOD and SCOD concentration were taken each day of the reactor operation and stored at approx. 4°C. NO_3^- and NO_2^- concentrations, TCOD and SCOD concentrations as well as DO and pH, TSS and VSS (bulk density) values in the reactor were measured according to procedures presented in Chapter 2, points 2.3.1 and 2.3.2.

Biofilm samples for thickness and density measurments (TS and VS) were collected from the membrane surface. The module with biofilm was removed from the reactor for 1 – 2 min and placed in vertical position to allow excess water to drain. Samples of known surface area were removed from module with a wooden spatula and put into a 5ml plastic syringe which was partially filled with de-ionized water and sealed. The biofilm

thickness and density were determined according to procedure described in details in Chapter 2, point 2.3.3.

Samples of the biofilm used for porosity determination were cut out together with the membrane module and embedded according to procedure suggested by the embedding kit supplier, Canemco Inc. The procedure was described in detail in Chapter 2, point 2.3.3. The embedded samples were then cut into slices with glass knife on a microtome. Series of parallel sections with 2 microns thickness were made so to cover all depth of the biofilm. The morphology and spatial distribution of microorganisms in the biofilm were amplified by staining with toluene blue and methylene blue. Obtained slices were studied with the Nikon Eclipse E400 light microscope and Image - Pro Plus software for image analysis.

3.3 RESULTS AND DISCUSSION

3.3.1 Efficiency of autotrophic denitrification in MBfR treating synthetic groundwater

Figure 3.1 demonstrates the reproducibility of denitrification over several operational cycles. With the exceptions of the periods where mixing and dissolved oxygen concentrations were varied to examine their effects on performance, the reactor provided consistent nitrate removal, with residual nitrate concentration below 2 mg l^{-1} at the end of each cycle. Also, following the artificial disturbances introduced by the operator, the denitrification efficiency promptly returned to its original level. The obtained average denitrification rate was equal to 1.05/-0.09 gNO_3-N m^{-2} d^{-1} (95% CI 1.02 to 1.08 gNO_3-N m^{-2} d^{-1}) . The maximum NO_3^- flux to the membrane was equal to 1.76 gNO_3-N m^{-2} d^{-1}

which was only slightly lower then values of 2.0 gNO_3-N m^{-2} d^{-1} and 2.5 gNO_3-N m^{-2} d^{-1} obtained by Gantzer (1995) and Ergas et al. (2001) respectively. As expected, the denitrification rates obtained were lower then those reported (4 gNO_3-N m^{-2} d^{-1}) for heterotrophic denitrification systems using methanol as an electron donor.

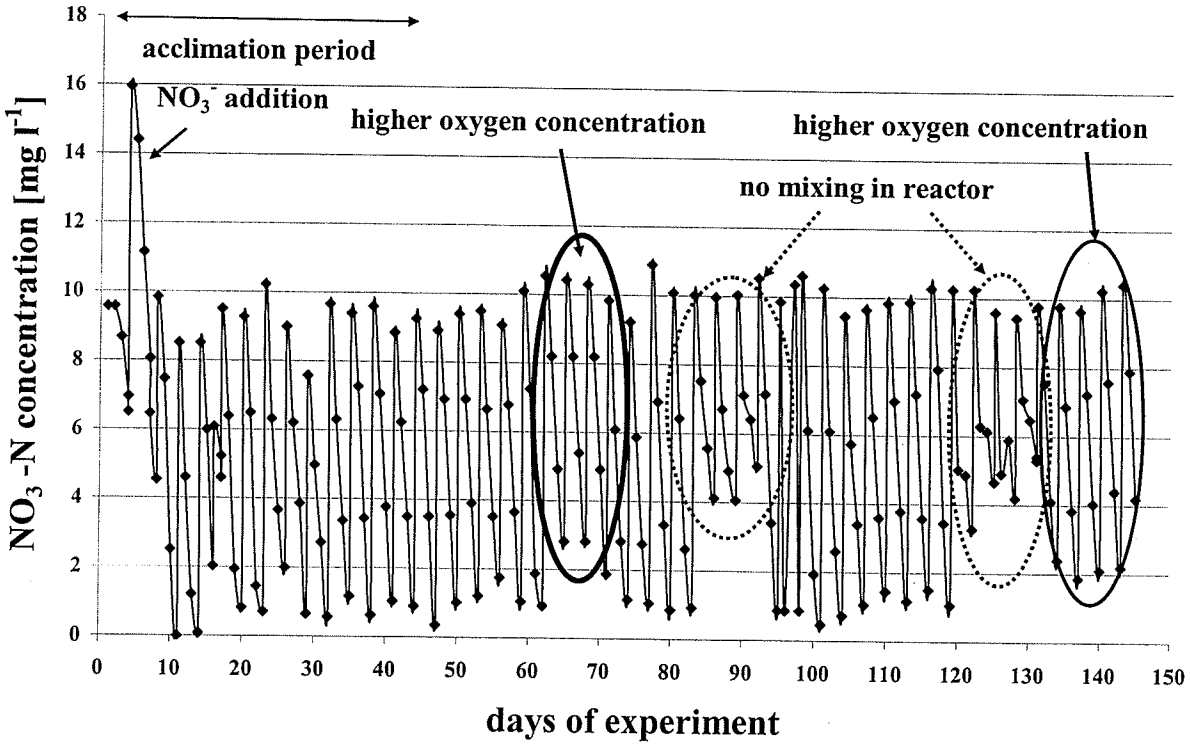


Figure 3.1 Nitrate concentrations during the entire experimental period

3.3.2 Influence of shearing stress and substrate mass transport

It appeared that for well established biofilm (ca. 500 μm) the main limiting step of the process was the mass transport (both advective and diffusive) of nitrate towards and into the biofilm. The higher nitrate concentrations in the solution related to higher nitrate removal rates (Figure 3.2 (b)). The removal rates during first two days of the cycle were 1.2 +/- 0.31 gNO_3-N m^{-2} d^{-1} (95% CI 1.05 to 1.32 gNO_3-N m^{-2} d^{-1}) and 0.98 +/- 0.46 gNO_3-N m^{-2} d^{-1} (95% CI 0.78 to 1.18 gNO_3-N m^{-2} d^{-1}) respectively. Nitrate concentration

became the limiting factor and as the concentration gradient decreased the denitrification rate decreased with each day of the cycle. The removal rate on the last day of the cycle was only around 0.67 +/- 0.21 gNO_3-N m^{-2} d^{-1} (95% CI 0.58 to 0.76 gNO_3-N m^{-2} d^{-1}) (Figure 3.2 (b)).

The limiting conditions of nitrate concentration and mass transport were further confirmed by examining the effect of mixing in the reactor. During periods of time when bulk mixing was stopped (Figure 3.1), denitrification rates were significantly reduced as the nitrate transport to the biofilm was slower. Average nitrate removal efficiency in reactor decreased by 36.8 % to an average of 0.66 +/- 0.1 gNO_3-N m^{-2} d^{-1} (95% CI 0.56 to 0.75 gNO_3-N m^{-2} d^{-1}) when no mixing was provided.

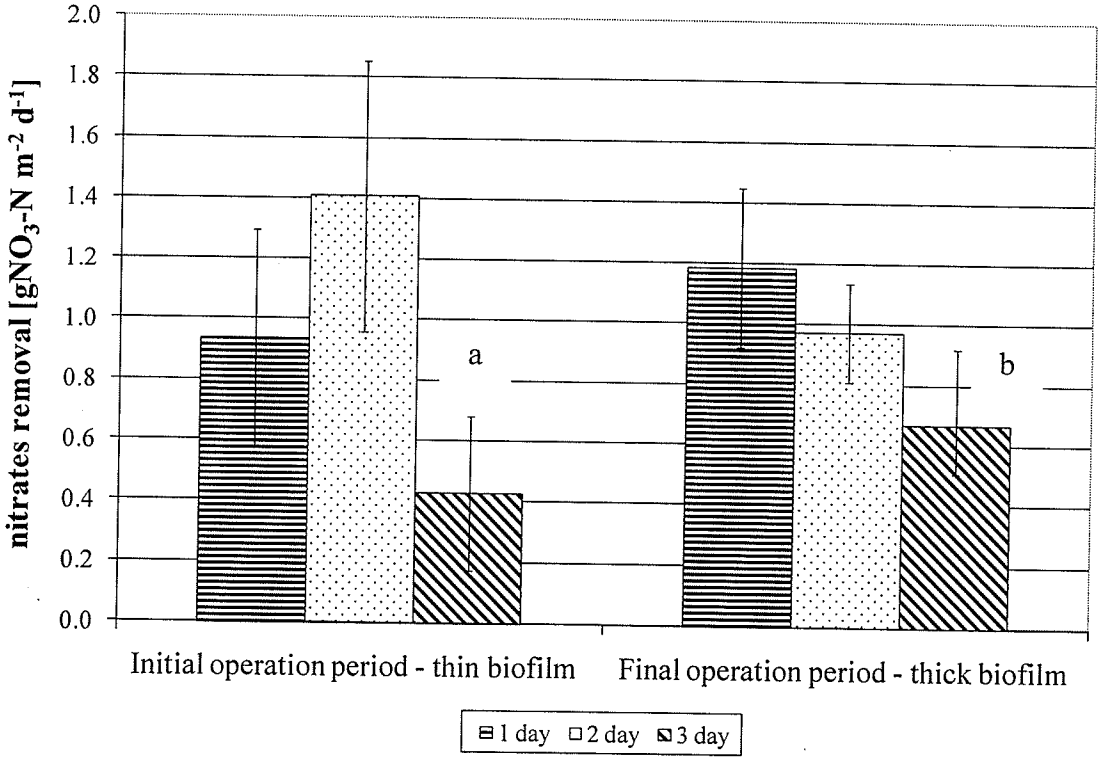


Figure 3.2 Nitrate removal during 3 d of cycle for thin (150 μm) and thick (500μm) biofilm (200 rpm each mixer; DO values on following days of the cycle: 6.8; 3.6, 3.5, 2.3 mg O_2 l^{-1}), mixing provided

Note: initial period (a) – 6 replicates; final period of operation (b) 15 replicates

3.3.3 Effect of DO on autotrophic denitrification within biofilm

Oxygen concentration in the bulk varied depending on the progression of the fill-draw cycle, starting from 6.8 mg O_2 l^{-1} on first day, and averaging 2.33 mg O_2/L on the last day of the cycle. The DO concentration on following during four days in cycle were equal to 6.8 +/- 0.7; 3.6+/- 1.0, 3.5+/- 1.0, 2.3+/-1.3mg O_2 l^{-1}. Although the oxygen concentration was outside the optimum range for denitrification, the process continued due to the attached growth conditions and the fact that the hydrogen was coming from the membrane fibre underneath the surface of the biofilm.

Testing showed that the denitrification process was strongly influenced by dissolved oxygen, nitrate concentration in the bulk and changing biofilm parameters such as thickness and density. In the beginning of the experiment, when the thickness of the biofilm was small (Figure 3.2 (a)) nitrate removal process was strongly affected by oxygen concentration in the bulk. Despite high nitrate concentration the removal rate was equal to only 0.94+/- 0.3 g NO_3-N l^{-1} (95% CI 0.56 to 1.31 gNO_3-N m^{-2} d^{-1}) (DO= 6.8 +/- 0.7 mg l^{-1}). As the oxygen concentration was decreasing during the three days cycle, nitrate removal was significantly increasing. The removal rate on day second of the cycle was equal to 1.4 +/- 0.4 g NO_3-N l^{-1} (95% CI 1.03 to 1.78 gNO_3-N m^{-2} d^{-1}) (DO = 3.6 +/- 1.0 mg l^{-1}). However in contrast to suspended culture processes, the biofilm population showed higher resistance to adverse conditions. When the thickness of biofilm increased (to around 500μm), the influence of the oxygen in the bulk diminished significantly leading to improved nitrate removal (Figure 3.2 (b)).

Despite good resistance to high dissolved oxygen concentrations, lasting concentrations higher than 4 mgO_2 l^{-1} (through 3 days of the cycle), inhibited the process, decreasing

nitrate removal by some 12%, from an average of 1.05 +/-0.09 gNO_3-N m^{-2} d^{-1} to 0.93 +/- 0.02 gNO_3-N m^{-2} d^{-1} (95% CI 0.91 to 0.95 gNO_3-N m^{-2} d^{-1}). The influence of dissolved oxygen concentration is shown on Figure 3.1.

3.3.4 VSS and TSS in the treated bulk (bulk density)

The measurement of the bulk density (TSS and VSS) was carried out in order to investigate the activity of suspended biomass. The tests of the activity of the suspended biomass present in the bulk liquid (i.e. the analysis of potential denitrification carried by the bacteria suspended in the solution) of the biofilm reactor proved that most of the denitrification was carried out by the biofilm population. The ratio of VSS/TSS in the bulk liquid showed a decreasing trend over the duration of testing (Figure 3.3), while nitrate removal was occurring, which was indicative of the activity of microorganisms in the biofilm. The average values of TSS and VSS in solution in the beginning and end of cycle are shown in Table 3.3.

Table 3.3 Average values and standard deviation values for TSS and VSS in the bulk liquid solution at the beginning and end of each cycle

Parameter, Unit	Beginning of Cycle, System Influent	End-of-cycle, System Effluent
TSS, mg l^{-1}	78.6 (+/- 40)	72.3 (+/- 41)
VSS, mg l^{-1}	25.2 (+/- 13)	24.4 (+/-15)

The analysis of VSS values in the beginning and in the end of the cycle showed similar values (Table 3.3) so it can be concluded that biomass shearing was not significant. In

fact the difference in TSS was larger than VSS indicating that removal of inorganic substances present in the feed (such as K_2HPO_4 or KH_2PO_4) was occurring. These substances were also incorporated in the biofilm structure which was confirmed by the microscopic observation of crystallized substances in the biofilm.

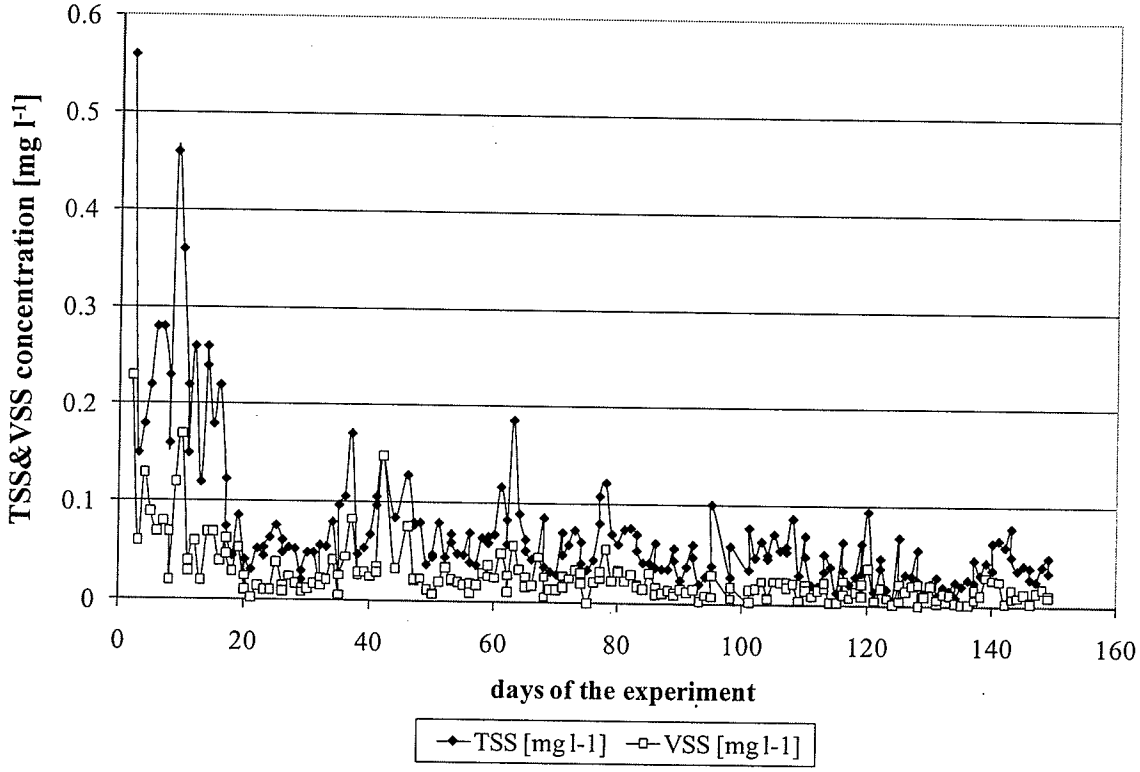


Figure 3.3 TSS and VSS concentrations in the treated solution

3.3.5 Biofilm parameters

3.3.5.1 Biofilm thickness and density

For this portion of the study, samples of well established biofilm, starting from the 59th day of the experiment were used. The analysis was carried out either weekly or every second week. Biofilm thickness and density are presented in Figures 3.4 and 3.5(a) and

3.5(b), respectively. Vertical bars denote the standard deviation observed during each measurement. The evaluation of impact of mixing and thereby shear stress suggests that the low shear stress results in a increase of average biofilm thickness and a drop in biofilm density (Figure 3.6). The biofilm thickness increased from 734 +/- 243 μm (95%CI 604 to 863 μm) to 1017 +/- 250 μm (95%CI 540 to 1494 μm) when mixing was eliminated. Contrary changes were observed for biofilm density. It decreased from 179+/- 83 g TS l^{-1} (95% CI 135 to 223 g TS l^{-1}) to 91+/- 20 g TS l^{-1} (95% CI 59 to 123 g TS l^{-1}) and from 64+/- 30 g VS l^{-1} (95% CI 48 to 79 g VS l^{-1}) to 32+/- 14 g VS l^{-1} (95% CI 15 to 48 g VS l^{-1}). This indicates that the change in biofilm structure was not related to biomass growth but to the hydraulic conditions at the biofilm surface.

Another important observation was related to biomass sloughing. When the biofilm thickness reached the value limiting nitrate mass transfer decreased removal rates were observed and sloughing took place at around day 70 (Figure 3.4). Decreased shearing stress accompanied by the increase in biofilm thickness and drop in biofilm density led to similar observations of sloughing. On day 90 and 137 after re-introducing mixing into operating mode shearing of outer layers was observed (Figure 3.5(a) and 3.5(b)). The decrease in total solids density was more significant then in volatile solids density (Figure 3.5(a), 3.5(b) and 3.6). This indicates that, sloughing material was mostly nonbiological. The ratio of volatile solids to total solids within biofilm increased after sloughing from 0.31 to 0.41. This process was probably connected to the structure and composition of the biofilm. The bacterial colonies (organic matter, expressed by VS density) were located close to the membrane surface, while minerals precipitated on the external layers (inert solids, expressed by difference between total and volatile solids). The organic compounds

provide for material binding the inorganic fraction of the biofilm. The increase in inert solids with simultaneous unchanged organic content could deteriorate biofilm stability. This interpretation was confirmed by detected changes in VS/TS ratio (Figure 3.7) and during microscopic observations with the pictures of embedded membrane membrane – biofilm sample (Figure 3.8).

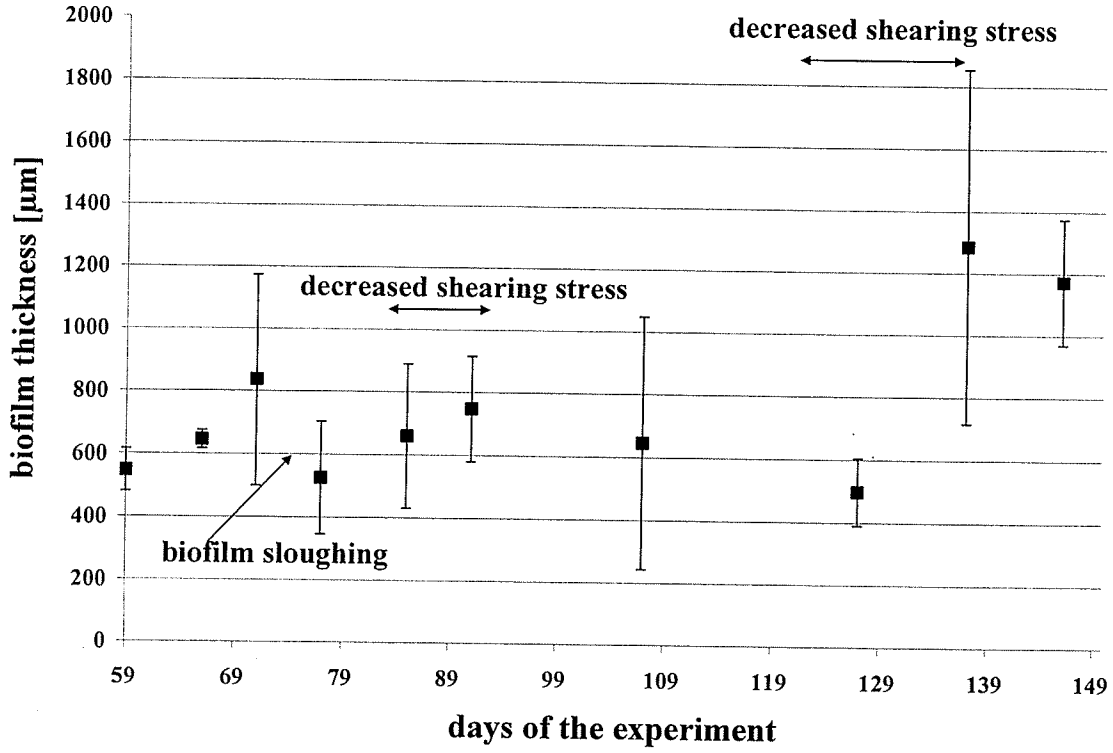
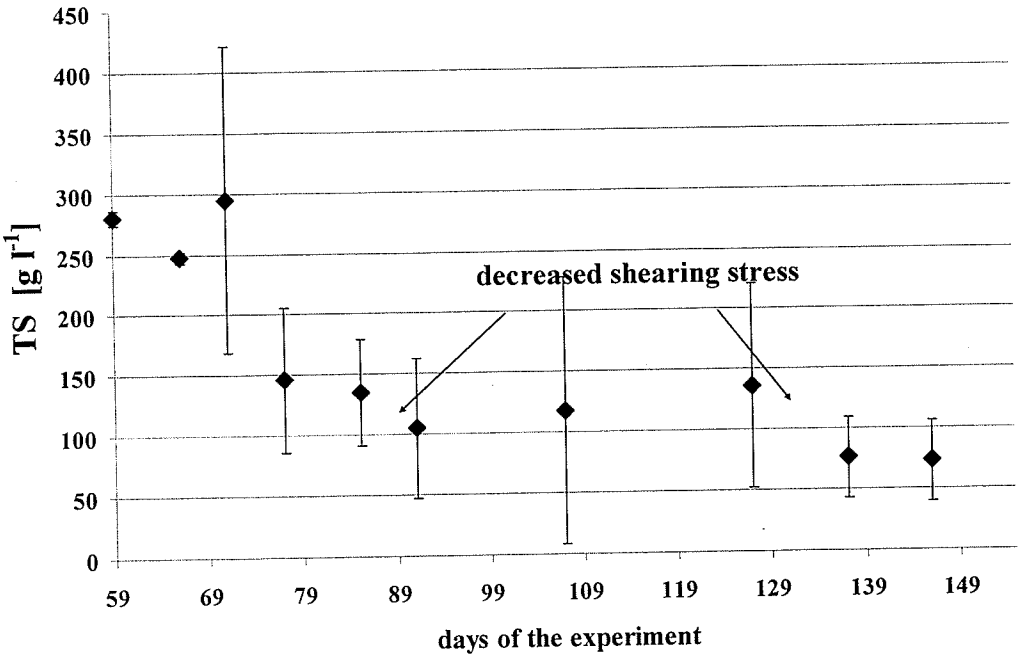


Figure 3.4 Biofilm thickness changes

(a) density expressed by TS content



(b) density expressed by VS content

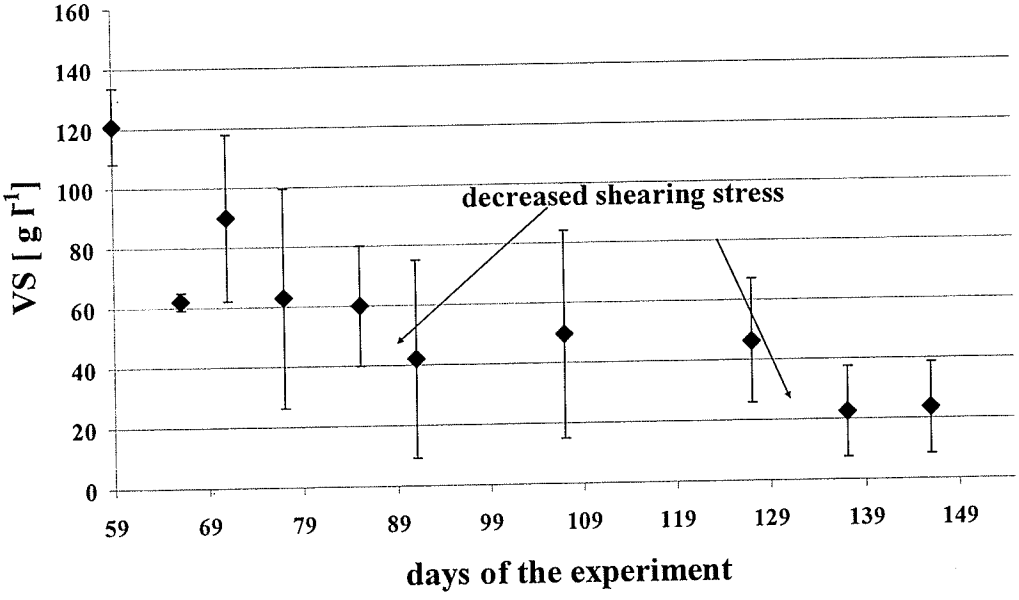


Figure 3.5 Changes of biofilm density

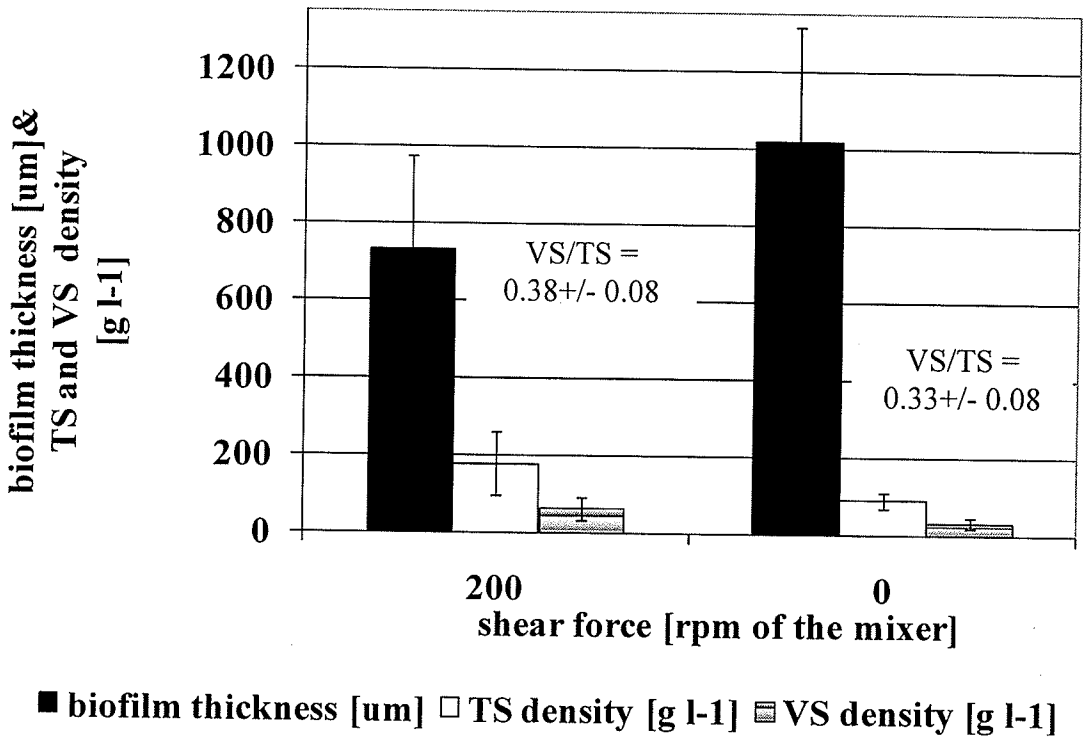


Figure 3.6 Relatioship between shear force and biofilm parameters (16 replicates per each phase)

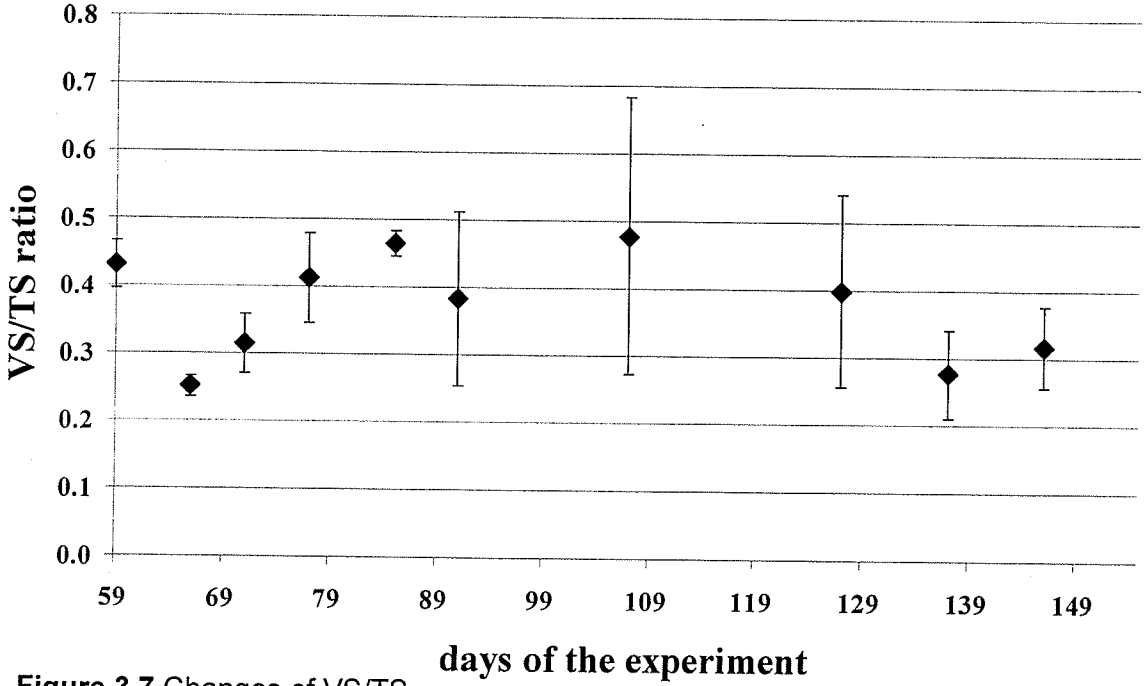


Figure 3.7 Changes of VS/TS

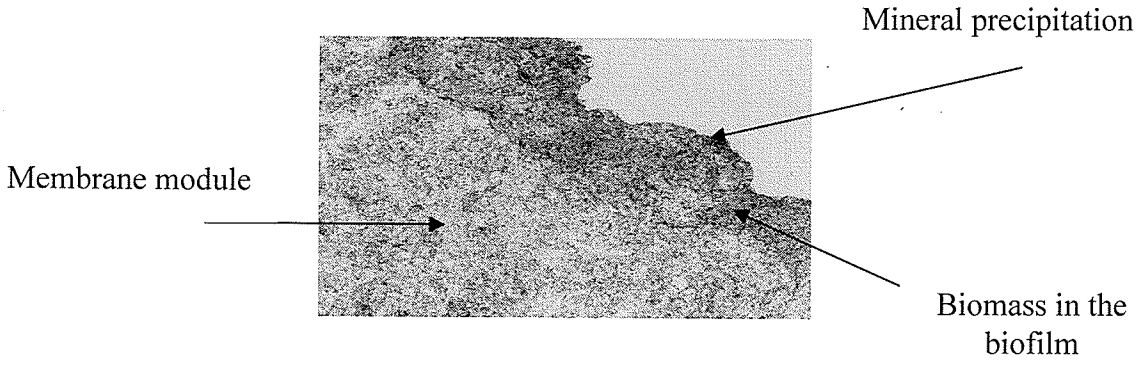


Figure 3.8 Vertical slide of the embedded membrane – biofilm sample

3.3.5.2 Biofilm composition and porosity

Biofilm composition analysis and porosity were determined at the end of the testing period. It was not possible to analyze for these parameters during reactor operation, as the procedure required the destruction of the module. Microscopic analysis of samples, revealed the presence of higher organisms in the biofilm. Most of them were rotifers, which were present in the upper layers of the biofilm, where the praying environment, dissolved oxygen concentration and mobility are optimal. Figure 3.9 shows the rotifers grazing at the aggregates of bacteria. The higher organisms' existence in the biofilm structure affects the biofilm accumulation. On the other hand their presence increases the transport of nutrients to deeper biofilm layers by increasing biofilm porosity (Ganczarczyk and Zahid, 1994).

Analysis of the bacteria cells organization confirms that, for thick biofilms, bacteria in lower layers tend to create clusters more readily than those situated in outer strata. In deeper layers of the biofilm excreted by bacteria extracellular polymeric (EPS) substances allow for creation of aggregations. The current study, confirmed the

observation as the clusters appeared closer to the membrane surface (deeper layers of biofilm). Figure 3.10 (a) and 3.10(b) shows comparison of the outer and deeper layers of the biofilm. The changes of the porosity along the depth of the biofilm are presented in Figure 3.11 which shows that porosity (the ratio of the area of the pores to the total area of the section) decreased with depth in the biofilm, which can be attributed to the presence of larger size clusters (see Figure 3.10). Analysis revealed that porosities closer to the membrane surface (~24 %) are almost 40% less than in the upper strata of biofilm (61%). The slight increase of biofilm porosity in strata close to the module can be associated with formation of either hydrogen bubbles (small defects of the diffusive odule) or nitrogen bubbles created during intensive denitrification.

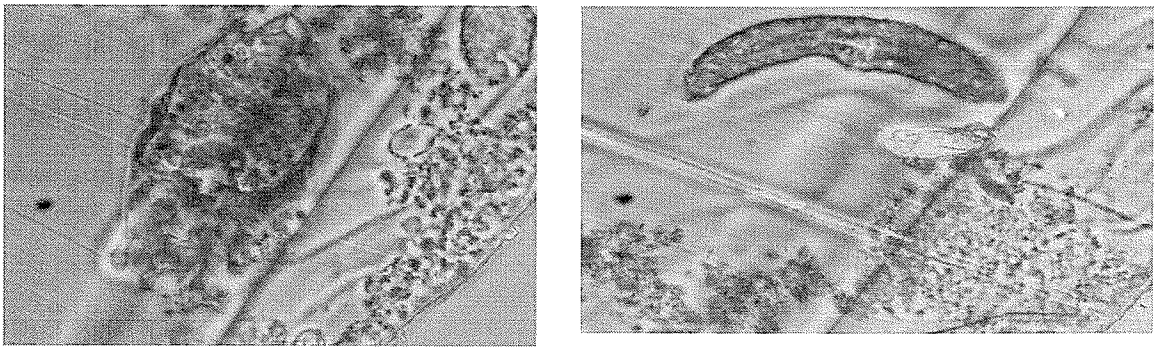
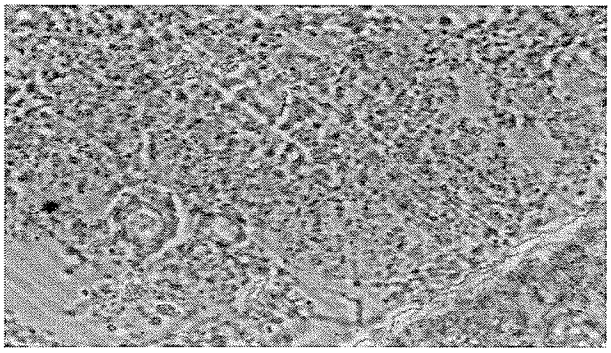


Figure 3.9 Rotifers preying at the bacteria aggregates

(a) outer layer (60 μm depth)



(b) deeper layer (400 μm depth)

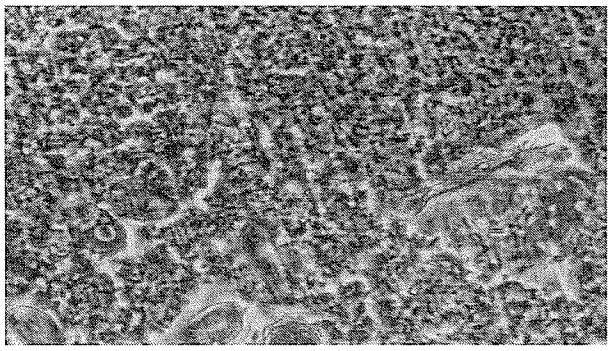


Figure 3.10 Bacteria cells organization in outer (a) and deeper (b) layers of the biofilm

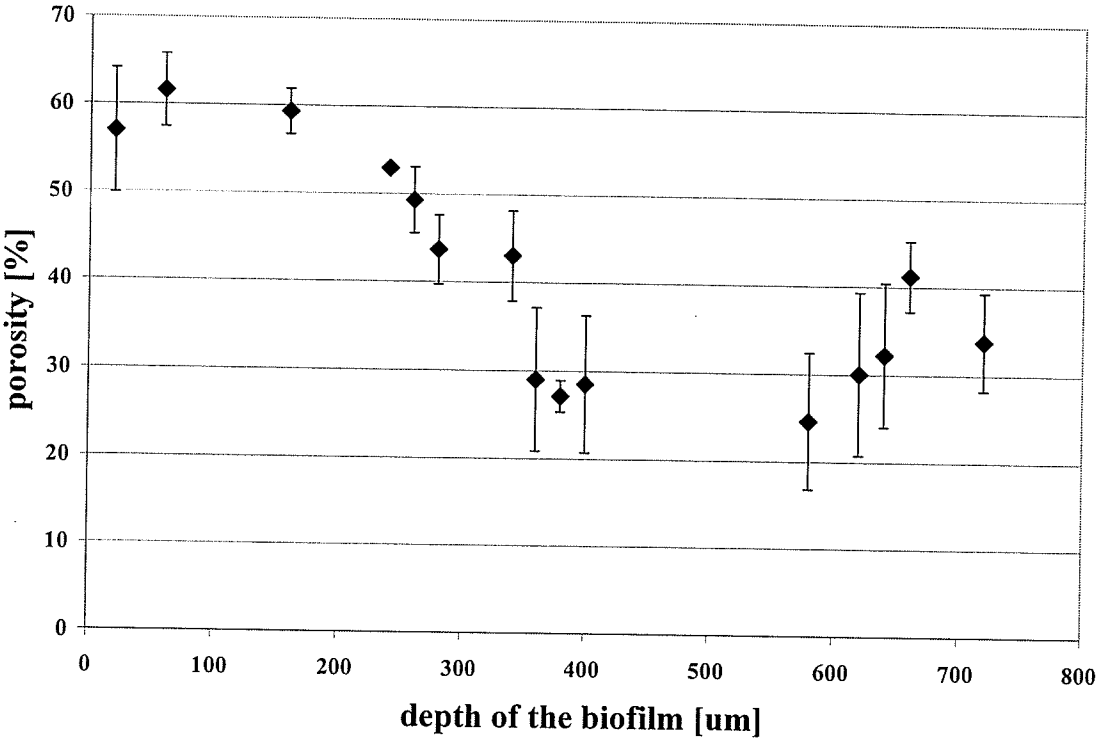


Figure 3.11 Changes of the porosity with the increasing depth of the biofilm

3.4 CONCLUSIONS

A flat sheet hollow fiber membrane biofilm reactor was operated for hydrogen-driven denitrification of ground water over a period of 145 days. During the 60 day start – up period, a biofilm developed on the membrane surface and steady-state operation was established. The following observations were made: Conclusions

1. Average denitrification rate was equal to 1.05+/- 0.09 gNO_3-N m^{-2} d^{-1}, while the maximum NO_3^- flux to the membrane was equal to 1.76 gNO_3-N m^{-2} d^{-1}.

2. Shear force had crucial impact on denitrification rates as average nitrate removal efficiency decreased by 36.8 % to 0.66+/-0.1 gNO_3-N m^{-2} d^{-1} when no mixing was provided due to observed changes in biofilm structure and diminished nitrate diffusion.

3. Application of higher shear-stress led to the creation of a more compact biofilm and thereby reducing the risk of rapid sloughing total and volatile solids as well as COD breakthrough in the effluent.

4. The biofilm showed resistance to high dissolved oxygen concentrations and only consistently higher concentrations than 4 $mgO_2\ l^{-1}$ inhibited the process, decreasing nitrate removal by some 12%.

CHAPTER 4: HYDROGEN LIMITATION- A METHOD FOR CONTROLLING THE PERFORMANCE OF MEMBRANE BIOFILM REACTOR FOR AUTOTROPHIC DENITRIFICATION OF WASTEWATER[3]

4.1 INTRODUCTION

4.1.1 Microorganisms growth under starvation conditions

The availability of nutrients influences species composition and community performance. Biological growth and generation of EPS depends on the substrate (Food) to the microorganism (M) ratio or F/M ratio (Cho et al. 2005). Microbial growth can occur in substrate - limited or substrate - sufficient conditions according to the relative availability of the substrate (carbon and energy source) and other nutrients (Zeng and Dekwer, 1995). The consumption rates are higher under substrate sufficient conditions than under substrate limitation, as overall quantity of substrate consumed is associated with utilization for growth, utilization for maintenance and utilization due to energy spilling (Russell, 2007).

Specific substrate utilization rate	=	Substrate utilization for microbial growth	+	Substrate utilization for maintenance	+	Substrate utilization due to energy spilling

The most common model for substrate utilization (r_s) is based on the Michaelis-Menten kinetics (eq.4.1)

[3] Parts of this chapter were published in *Water Science and Technology*, 2006; 54(9) 165-72
Hydrogen limitation – a method for controlling the performance of membrane biofilm reactor for autotrophic denitrification of wastewater.
D.Celmer. J.Oleszkiewicz, N. Cicek, H. Husain

$$r_{su} = -\mu_{\max} * S * X / Y * (K_s + S) = -k * S * X / (K_S + S)$$

$$k = \mu / Y_{\max} \qquad (4.1)$$

Where: μ_{max} – maximum specific growth rate;

S – concentration of limiting substrate in the solution;

X – biomass concentration;

Y – maximum yield coefficient;

K_s – half velocity constant;

k- max rate of substrate utilization per mass unit.

The yield coefficient was initially taken as constant however it can be affected by specific growth yield at certain conditions. The maintenance model created by Pirt (1975) accounts for this effect.

$$k = \mu / Y_{\max} + m_s \qquad (4.2)$$

where: m_s- substrate required for maintenance

The observed growth of the biopopulation in substrate limited conditions will be diminished as the result of lower substrate utilization rate and lower maximum specific bacterial growth rate. It will also depend on endogenous decay which occurs in colony. The net growth rate can be calculated according to the following equation:

$$r_g = -Y * r_{su} - k_d * X \qquad (4.3)$$

where: r_g- net growth rate;

k_d- endogenous decay coefficient.

Thus there will not be any observed biomass growth when:

$$-Y * r_{su} = k_d * X \tag{4.4}$$

The excess biopopulation growth can be then limited by creating substrate limited conditions and lowering substrate utilization rate. Low F/M ratio can help creating stable biopopulation. Restriction of specific nutrients is used in many biotechnological processes to induce and optimize the microbiological formation. Usually one specific nutrient restricts the maximum quantity of the biomass that can be produced, whereas all other nutrients are available in excess (Egli and Zinn, 2003). Results obtained by Hunt et.al. (2004) supported the idea that starvation conditions are environmental conditions that stimulate a release of microbes form the biofilm. Rochex and Lebeault (2004) found that increased nutrient concentration caused increased rate and extent of biofilm accumulation, while Kim and Fogler (2000) observed that starvation conditions slower the growth of the biofilm.

4.1.2 EPS accumulation under starvation conditions

The other organic components of the biofilm are EPS (extracellular polymeric substances) and SPM (soluble microbial products). EPS matrix consists usually of large quantity of polymeric substances located at or outside the cell surface. EPS are defined as those substances that are associated with the cell either in form of a tightly bound capsule or as loosely associated polymers. SMP are soluble cellular components that are released during cell lysis or are excreted for some purpose. As they are a result of substrate metabolism they can be either substrate utilization associated products (UAP) or biomass

associated products (BAP). EPS and SMP are then microbially produced organic material that contain electrons and carbon, but are not part of the active mass. If significant part of electron-donor demand is shunted to EPS and SMP production there is not enough energy for synthesizing active biomass and thus active biomass yield and specific growth rate decline (Laspidou, 2003).

The amounts of EPS are controlled by active secretion, shedding of cell surface material (cellular debris), cell lysis and hydrolysis products, products of extracellular activity. In addition, EPS can contain a variety of sorbed substances such as pollutants and incorporated particulate matter and residues of the dead cells. The broadest possible definition of EPS states that they include polysaccharides, proteins (including enzymes), DNA, lipids and uronic acid, which act as a matrix to bind covalent cations (Speath and Wuertz, 2000).

The active secretion of the EPS is believed to depend on the rate of substrate utilization. Some researchers state that less EPS is produced during growth and rapid substrate consumption (Evan et al., 1994, Robinson et al., 1984). Others claim that EPS production is proportional to substrate utilization and growth rate (Turakhie and Charaklis, 1988). According to Williams (1974) it is independent of growth rates. It seems that this feature varies for different kind of microorganisms. However the main rules of kinetics of EPS formation have to include growth – associated EPS formation, non- growth associated EPS formation and finally EPS lost due to dissolution and hydrolysis processes. The EPS formation rate can be expressed in the following equation (Hsieh at all. 1994):

$$r_p = u_p * \left(S / K_p + S \right) X_a + f_{xp} * k_d \left(K_d / K_d + S \right) X_a - u_{pdiss} \left(P / X_a \Big/ \left(K_{pdiss} + P / X_a \right) \right) \quad (4.5)$$

Where: r_p- EPS formation rate;

u_p – the maximum specific bound EPS production rate;

K_p – the corresponding half- maximum rate concentration for substrate;

f_{xp} – fraction of biomass that is converted to EPS;

k_d – the biomass decay coefficient;

K_d – the substrate concentration that reduced decay coefficient to one half of k_d;

u_{pdiss} – the maximum specific rate of the bound EPS degradation (by hydrolysis or dissolution);

P – the concentration of the bound EPS;

K_{pdiss} – the ratio of P/X giving one half of the maximum rate;

X_a – active biomass.

Thus it can be concluded that EPS do not accumulate when the first order decay rate of EPS (hydrolysis / dissolution) is faster then the decay rate of active biomass. EPS synthesis and active secretion is limited by lowering substrate utilization rate.

The reported values of EPS production vary in the range of 100–700 mg EPS (g VS) $^{-1}$ (Guibaud et al., 2005). As in any biological process only the surplus EPS production is undesirable. Some EPS are needed as "glue" for bacterial mass (Speath and Wuertz, 2000). Their presence might be essential for cell survival as EPS capsules impart a certain resistance to shearing forces and thus create a protective zone. Within a biofilm EPS create protective layers that cushion microorganisms from adverse conditions such as pH value extremes, hydraulic pressure, desiccation (Flemming, 1991) thus creating a

population which is able to withstand a wide range of conditions (Speath and Wuertz, 2000). On the other hand, as the EPS created in biofilm typically form tightly bound capsules - they can also inhibit diffusion of substrates.

EPS production exerts significant influence on bacterial growth and on biofilm structure and function (Kreft and Wimpenny, 2002). Excess EPS production leads to a decrease in the growth of the producers, and increase in the patchiness and roughness of the biofilm, and a decrease in porosity (Kreft and Wimpenny 2002).

Biological growth and EPS accumulation depends on the substrate to microorganism loading or F/M ratio (Cho *et al.* 2005). Low F/M ratio inhibits the microorganism growth and EPS accumulation. Creating starvation conditions, due to limited supply of hydrogen should inhibit microorganism growth and excess EPS production, preventing an increase in biofilm thickness and density.

4.1.3 Limiting the minerals precipitation by low pH

The biofilm is also composed of inorganic substances. In many cases the entrapped particles and precipitates are major biofilm components. High concentrations of inorganic matter lead to the inhibition of the biofilm activity and process efficiency. Thus, stabilized MBfR performance can be achieved only with controlling the inorganic biofilm content.

The precipitation of the minerals present in the treated wastewater is an important issue during the denitrification process. During the process one equivalent of alkalinity is produced per equivalent of NO_3^- N reduced. This equates to 3.75 g of alkalinity as $CaCO_3$ per gram of nitrate nitrogen reduced (Metcalf& Eddy, 2004). Increase of pH leads

to the production of OH^-, CO_3^{-2}, S^-, which can produce insoluble species with metal ions (Remoudaki et al., 2003; Petrucci and Harwood, 1993).

The carbonate buffer system is one of the most important buffer systems in water and wastewater treatment (Sawyer, 2003):

$$CO_2\,(g) \rightleftharpoons CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \rightleftharpoons 2H^+ + CO_3^{2-} \quad (4.6)$$

Precipitation occurring in the solution containing metal ions (such as calcium, magnesium) and carbonates (CO^{-3}) depend on the concentration of these ions as well as pH (Petrucci and Harwood, 1993).

The solubility and possible precipitation of different chemical substances can be calculated based on the solubility equilibrium and reaction quotient equation respectively (Petrucci and Harwood, 1993):

$$K_{sp} = [C^+] * [A^-] \quad (4.7)$$

Where: K_{sp} – solubility product constant;

C^+ – cations concentration;

A^- – anions concentration.

$$Q_{sp} = [C^+]_{initial} * [A^-]_{initial} \quad (4.8)$$

Where: Q_{sp} – reaction quotient constant;

C^+ – initial cations concentration [M];

A- – anions concentration [M].

If $Q_{sp} > K_{sp}$ the concentration of ions is higher than they would be in a super- saturated solution and excess salt will precipitate from the solution. When $Q_{sp} < K_{sp}$ the solution is

unsaturated. Metal solubility data are available in many sources (Petrucci and Harwood, 1993; USEPA, Wastewater Technology Fact Sheet – Chemical Precipitation, 2000).

As the solubility of metal compounds is pH dependent, controlling the pH can prevent its precipitation and keep the stable biofilm parameters and denitrification efficiency of MBfR. The metal compounds tend to be least soluble in alkaline solutions. For most of the metals the main precipitation occurs in the pH range 7.0 – 9.0, with the least solubility at pH around 8.0 (Lee and Sanders, 2003).

Autotrophic denitrification efficiency is also affected by the pH, although published information is not consistent. Lee and Rittman (2003) showed that the optimum denitrification occurred for the pH range of 7.7 – 8.6, with the maximum efficiency at pH = 8.4. Other researchers (Shin J.H. et al, 2005) stated that complete denitrification was achieved below 7.6, while pH > 7.8 inhibited the process. Due to resistance of biofilm populations to adverse conditions biofilm population might show lower sensitivity to the otherwise negative influence of sub- optimum pH values.

4.1.4 Objective

The objective of the study was to assess the performance of autotrophic denitrification of low organic carbon content wastewater within a biofilm growing on a hydrogen diffusing membrane. Specifically, the objective was to evaluate the consistency of the system operation and the possibility of controlling the denitrification rate, as well as biofilm parameters and stability by supplying limited amounts of electron donor (hydrogen). The impact of pH on performance and biofilm structure was assessed as well.

4.2 MATERIALS AND METHODS

4.2.1 Reactor Operation

The experimental set-up comprised of two, 3 L each, laboratory-scale biofilm reactors. The reactors (Figure 4.1) were operated in a continuous flow mode with hydraulic retention time (HRT) equal to 5 hr (reactor #1) and 4 hr (reactor #2). The bioreactors were seeded with a population of suspended culture of autotrophic denitrifiers on the first day of the operation. Hydrogen was delivered through a submerged fibre membrane module. A detailed description of the membrane is presented in Table 4.1. Both reactors were placed on magnetic stirrers.

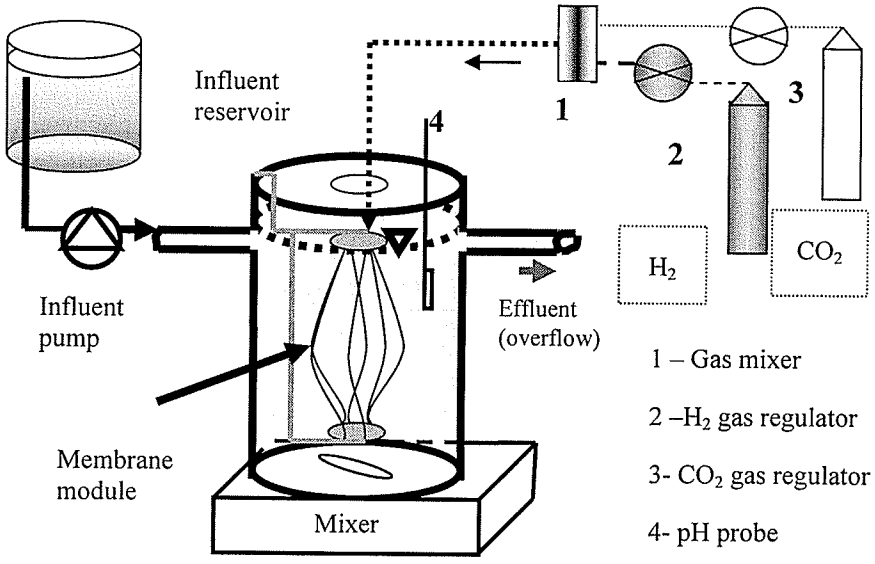


Figure 4.1 Membrane bioreactor set – up

Table 4.1 Description of the gas diffusing membrane

Charateristic Property	Value
	Fiber module
Manufacturer	Zenon Environmental Inc. GE Water & Process Technologies
Membrane material	polypropylen fibers
Hydrogen permeabilty	$1.34*10^{-11}$ mol/m^2/sec*m/kPa
Outer Diameter (OD) of fibers	58.17 µm
Inner Diameter (ID) of fibers	41.68 µm
Number of tows	80
Number of fibers per tow	70
Total number of fibers	5600
Fiber length	0.4 m
Membrane surface area	0.41 m^2

Testing was divided into acclimation and steady state operation periods. Synthetic wastewater which was used during the initial acclimation period provided the necessary nutrients in trace concentrations of $MnSO_4$, $FeSO_4$, KCl, CaCl, $MgSO_4$, ammonia, organic carbon, inorganic carbon, buffer substance and nitrate ($NaNO_3$). The initial influent nitrate concentration was equal to 15 mg NO_3-Nl^{-1}.The detailed composition of used wastewater is presented in Table 4.2

Table 4.2 Synthetic wastewater composition

Compound	Chemical formula	Concentration [mg l^{-1}]
Dipotassium hydrogen phosphate	K_2HPO_4	194
Manganese sulphate (heptahydrate)	$MnSO_4*7H_2O$	1.25
Ferrous sulphate (heptahydrate)	$FeSO_4*7H_2O$	0.56
Potassium chloride	KCl	1.75
Calcium chloride	CaCl	0.9
Magnesium sulphate (heptahydrate)	$MgSO_4*7H_2O$	12.5
Sodium nitrate	$NaNO_3$	78; 104;130[a]
Sodium bicarbonate	$NaHCO_3$	183
Beef extract	$C_{11}H_{11}N_5$	25
Yeast extract	$C_{22}H_{31}NO_5*2H_2O$	25
Ammonium chloride	NH_4Cl	12.5

[a] concentration of sodium nitrate for 3 tested nitrate loadings

Second period of the experiment included application of synthetic wastewater (SWW) and municipal wastewater (MWW) into reactors #1 and #2 respectively. Final effluent from a non-nitrifying wastewater treatment plant (North End Water Pollution Control Centre in Winnipeg, Canada) was used as real municipal wastewater (MWW). Nitrates were added to MWW in form of $NaNO_3$. The main parameters of used synthetic and municipal wastewater are presented in Table 4.3.

Table 4.3 Parameters of synthetic and municipal wastewater

Parameter	Units	SWW	MWW
SCOD	mg l^{-1}	85+/-31	47+/-23
alkalinity	mg $CaCO_3$ l^{-1}	196+/-29	311+/-58
temperature	C	22.8+/-1.9	20.8+/-2.7
DO	mg l^{-1}	0.21+/-0.17	0.20+/-0.14
pH	-	7.61+/-0.15	7.06+/-0.19

Three sets of influent nitrate concentrations were tested during three phases of the second period of the experiment (15, 20 and 25 mgNO_3-N l^{-1}) in order to simulate the impact of fluctuations in substrate concentration on the biofilm performance and its parameters. A constant hydrogen flow of 18 ml H_2 min^{-1} was kept through the three phases of the experiment. Theoretical hydrogen demand for the operational parameters should be low and in the range of 0.7 – 1. 56 ml H_2 l^{-1}. Some hydrogen was lost due to membrane defects (bubbles formation) leading to hydrogen-limited conditions. Increased buffer content (500 mg K_2HPO_4 l^{-1}) in synthetic wastewater and carbon dioxide application (1.5 ml CO_2 min^{-1}) into reactor #2 fed with MWW enabled evaluation of the impact of different methods of pH control on the denitrification process and biofilm structure (fourth phase).

4.2.2 Analytical Methods

Samples of influent and effluent for NO_3-N, NO_2-N and COD analysis were taken each day of the reactor operation and stored at approx. 4°C. NO_3 and NO_2 concentrations, COD concentrations as well as DO and pH, TSS and VSS values in the reactor and effluent were measured according to procedures presented in Chapter 2, points 2.3.1 and 2.3.2.

Biofilm samples for thickness and density were collected from the membrane surface. The module with biofilm was removed from the reactor for 10 min and placed in vertical position to allow excess water to drain. The samples of known surface area were removed from module with a wooden spatula and put into a 5ml plastic syringe which was partially filled with de-ionized water and sealed. The biofilm thickness and density was

determined according to procedure described in details in Chapter 2, point 2.3.3. EPS concentration was determined using the method of sequencing thermal treatment, centrifugation and acetone and ethanol precipitation (Morgan et all, 1990).

4.3 RESULTS AND DISCUSSION

4.3.1 Denitrification rates

Denitrification rates remained similar for both types of applied wastewater (SWW and MWW) and were independent of the nitrate concentration (Figure 4.2). The nitrate and nitrite removal were constant through all three phases of the second period of the experiment. The obtained nitrate removal values were equal to 0.50+/-0.02 g NO_3-N m^{-2} d^{-1} (95% CI 0.49 to 0.51 g NO_3-N m^{-2} d^{-1}) and 0.59/-0.04 g NO_3-N m^{-2} d^{-1} (95% CI 0.58 to 0.60 g NO_3-N m^{-2} d^{-1}) for reactors #1 and #2 respectively, regardless of changes in influent nitrate concentration.

The effluent contained relatively high concentrations of the nitrite (Table 4.4), which proved that hydrogen was the limiting factor in achieving full denitrification. The average nitrite was equal to 40% (+/- 14) % and 37% (+/- 3) % of total nitrogen (nitrate + nitrite) measured in the effluent from reactors #1 and #2 respectively. The effluent nitrate and nitrite concentration increased at the higher loadings – indicating the necessity of adding more hydrogen. Possible high nitrate and nitrite concentration in the effluent observed during increased loading of the MBfR seems to be major disadvantage of this control method.

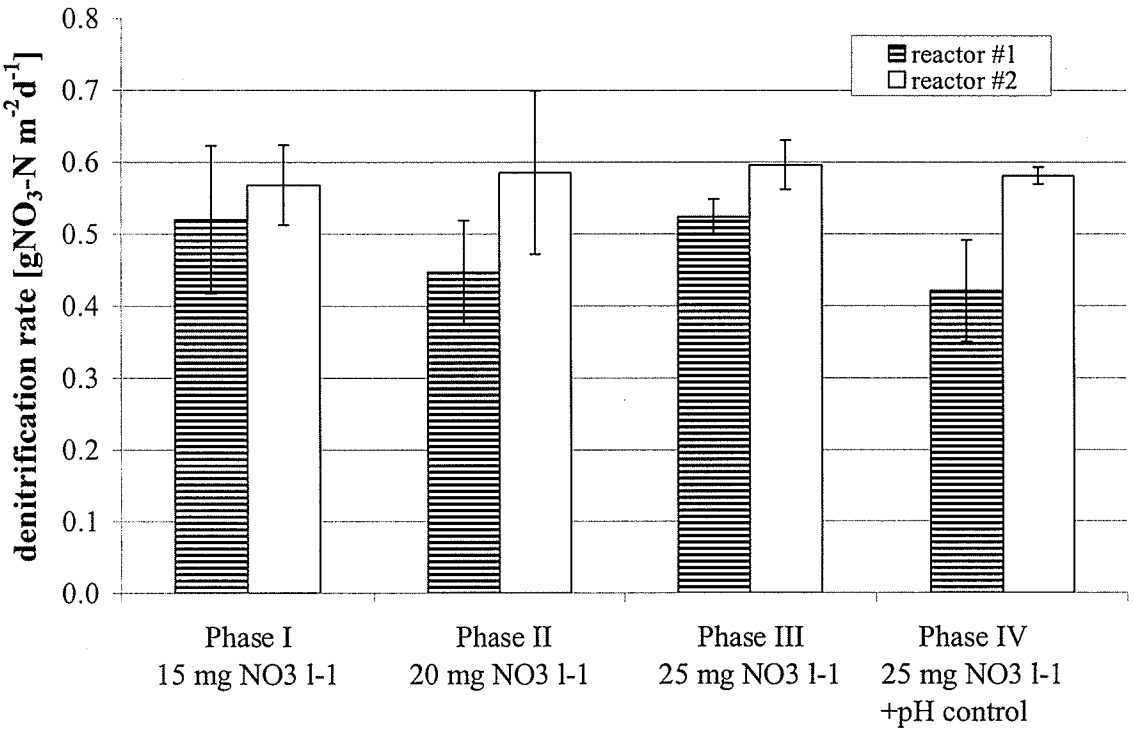


Figure 4.2 Denitrification rates for constant hydrogen flow (from 10 to 17 replicates per phase)

Table 4.4 Effluent quality

			15 mg NO_3 l^{-1}	20 mg NO_3 l^{-1}	25 mg NO_3 l^{-1}	25 mg NO_3 l^{-1} (buffer #1 and CO_2 #2)
parameter	reactor	units				
average influent concentration	#1	mg/L	16.6+/-3.6	18.7+\-0.6	24.9+/-0.6	23.9+/-0.9
	#2	mg/L	17.2+/-0.5	18.9+\-2.1	26.5+/-2.5	30.6+/-2.4
denitrification rate	#1	g/d*m^2	0.52+/-0.1	0.45+/-0.07	0.52+/-0.04	0.42+/-0.07
	#2	g/d*m^2	0.57+/-0.06	0.59+/-0.11	0.60+/-0.02	0.58+/-0.01
nitrate&nitrite removal	#1	g/d	0.20+/-0.04	0.17+/-0.03	0.20+/-0.02	0.16+/-0.04
	#2	g/d	0.23+/-0.02	0.24+/-0.05	0.24+/-0.03	0.24+/-0.09
reduction of nitrate &nitrite	#1	%	85.5+/-4.2	64.07+/-9.9	56.9+/-10.9	47.6+/-12.7
	#2	%	75.2+/-8.6	66.7+/-10.9	52.7+/-17.2	43.6+/-8.0
lowest achieved effluent	#1	mg/l	1.26	3.28	7.07	6.18
concentration	#2	mg/l	1.68	4.23	4.14	16.22
average effluent concentration	#1	mg/l	2.5+/-1.1	6.8+/-1.1	10.7+/-2.7	11.7+/-2.9
	#2	mg/l	4.3+/-1.5	6.4+/-2.4	12.5+/-5.4	17.35+/--3/3
average effluent	#1	mg/l	1.5+/-0.7	3.2+/-1.5	4.3+/-1.5	2.6+/-1.3
concentration	#2	mg/l	1.9+/-0.9	2.1+/-1.1	4.9+/-2.1	3.7+/-2.6
% nitrate in the	#1	%	54.6+/-9.1	43.6+/-12.7	40.6+/-14.6	20.7+/-9.5
effluent	#2	%	39.7+/-7.7	32.9+/-22.3	38.8+/-14.5	36.6+/-15.3

The obtained denitrification rates (Figure 4.2) are relatively low compared to the ones presented by Gantzer (1995) and Ergas et al., (2001) who cited 2.0 gNO_3-N m^{-2} d^{-1} and 2.5 gNO_3-N m^{-2} d^{-1}, respectively. Effluent quality and denitrification rates could most likely be increased by increasing the hydrogen utilization (minimizing the defects of the membrane). An increased gas partial pressure would improve hydrogen diffusion and its availability for the denitrification reaction.

Denitrification rates obtained in the fourth phase of the experiment showed the impact of two different pH control methods on the denitrification process. Application of the higher buffer concentrations led to a 20% decrease in denitrification rate, despite keeping the pH (pH= 8.6) close to the pH optimum of 8.4 as determined by Lee and Rittman (2003). It dropped from 0.52+/-0.02 (95% CI 0.49 to 0.54 g NO_3-N m^{-2} d^{-1}) to 0.42+/-0.07 g NO_3-N

m^{-2} d^{-1} (95% CI 0.37 to 0.48 g NO_3-N m^{-2} d^{-1}) after addition of buffer. Introducing carbon dioxide caused rapid decrease in the pH (to 6.95) however the denitrification rate remained unchanged. It dropped not significantly by only 4% from 0.60+/-0.01 g NO_3- N $m^{-2}d^{-1}$ at pH 8.5 (95% CI 0.58 to 0.61 g NO_3-N m^{-2} d^{-1}), to 0.58+/-0.01 g NO_3- N $m^{-2}d^{-1}$ at pH 6.95 (95% CI 0.57 to 0.59 g NO_3-N m^{-2} d^{-1}). No change in denitrification rate after addition of gaseous CO_2 suggest that concentration of inorganic carbon in MWW provided an excess source of carbon for autotrophic growth to occur.

4.3.2 TSS, VSS and COD in the effluent

Successful application of the tested membrane biofilm reactor for polishing the final effluent depends also on the obtained COD, TSS and VSS concentrations in the effluent. COD can be affected by VSS concentration and the excreted EPS. Stable operation of the biofilm means that constant biofilm thickness, density (TS and VS) and EPS production is achieved.

Throughout the study the effluent average TSS and VSS concentrations were around 11 mg TSS l^{-1} and 7 mg VSS l^{-1} for both of the reactors. Figure 4.3 present the consistency of the TSS and VSS concentrations in the effluents from one of the reactors. Most of the readings are below the required by Environment Canada concentrations of 20 mg l^{-1} and 35 mg l^{-1} required by UE. Infrequent sloughing of the biofilm indicated rather stable biofilm operation. Limitation of the hydrogen availability inhibited not only removal rate but also growth of the biofilm. The only major peak of TSS and VSS concentration for reactor # 2 were associated with increase in TSS and VSS concentration in influent wastewater.

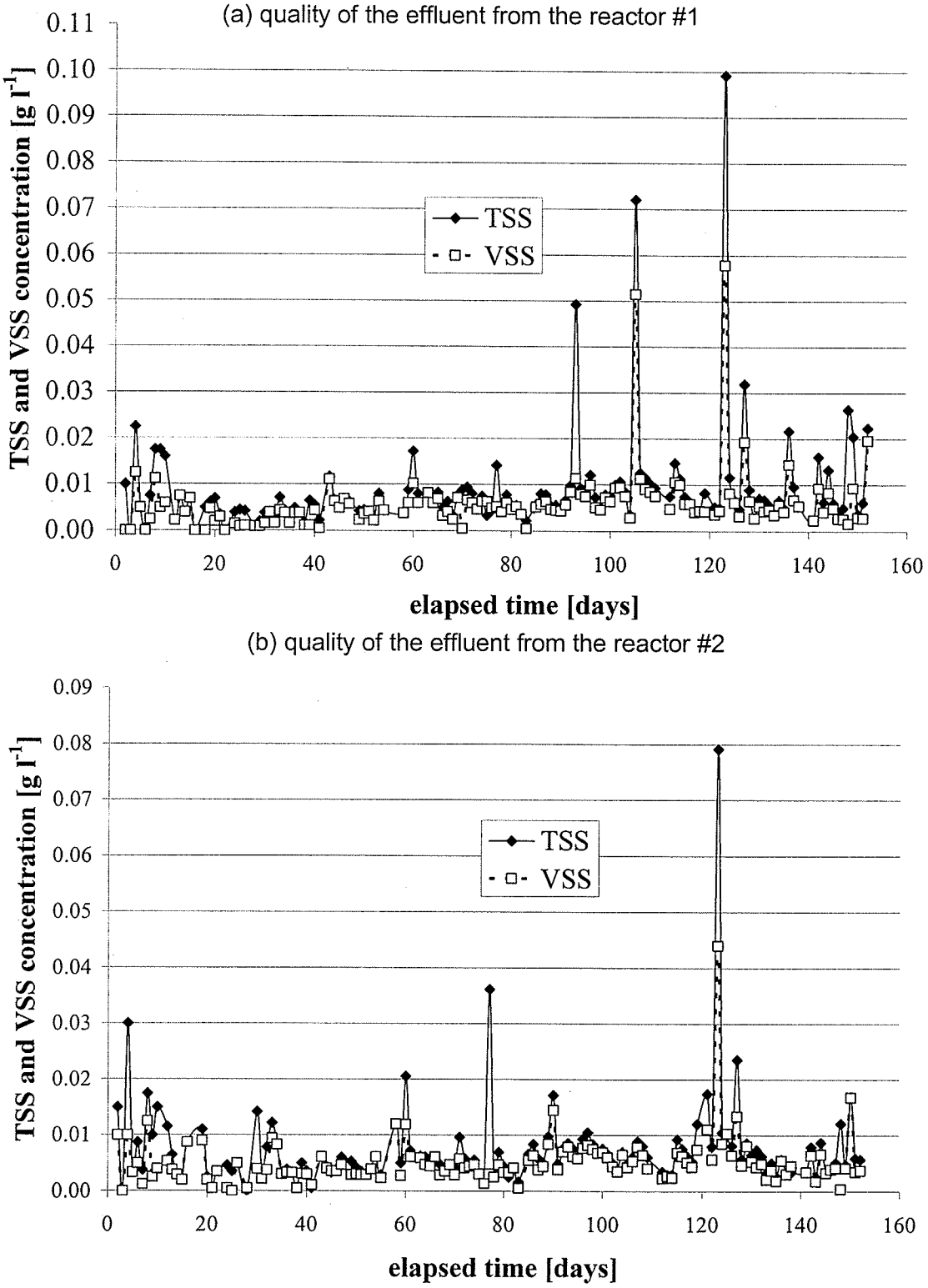


Figure 4.3 TSS and VSS concentration in the reactor #1 (4.3.(a)) and #2 (4.3.(b)) effluent

COD concentration in effluent was also monitored. As there was no increased sloughing of the biomass, the changes of the effluent COD concentrations were connected with changing influent concentrations. Figure 4.4 presents the average influent and effluent concentrations for both of the reactors. Synthetic wastewater applied to reactor #1, was composed of easily biodegradable COD (yeast and beef extract), while MWW wastewater (reactor #2) was obtained from final effluent, so it contained mostly non-biodegradable COD. The COD removal in reactor #1 was clearly visible in obtained results, proving co-existence of autotrophic and some heterotrophic bacteria within the biofilm. Total COD in the effluent from reactor #2 was slightly higher then the influent COD due to presence of low concentrations of VSS. Soluble COD remained similar to influent concentration proving that intensive EPS excreting did not appeared under starvation conditions.

For both wastewater types the effluent COD concentrations were in the same range and were lower than the UE requirements (125 mg O_2 l^{-1}; European Union directive 271/91/EWG.). The experiment proved that controlling biofilm growth prevents increase in COD effluent concentrations.

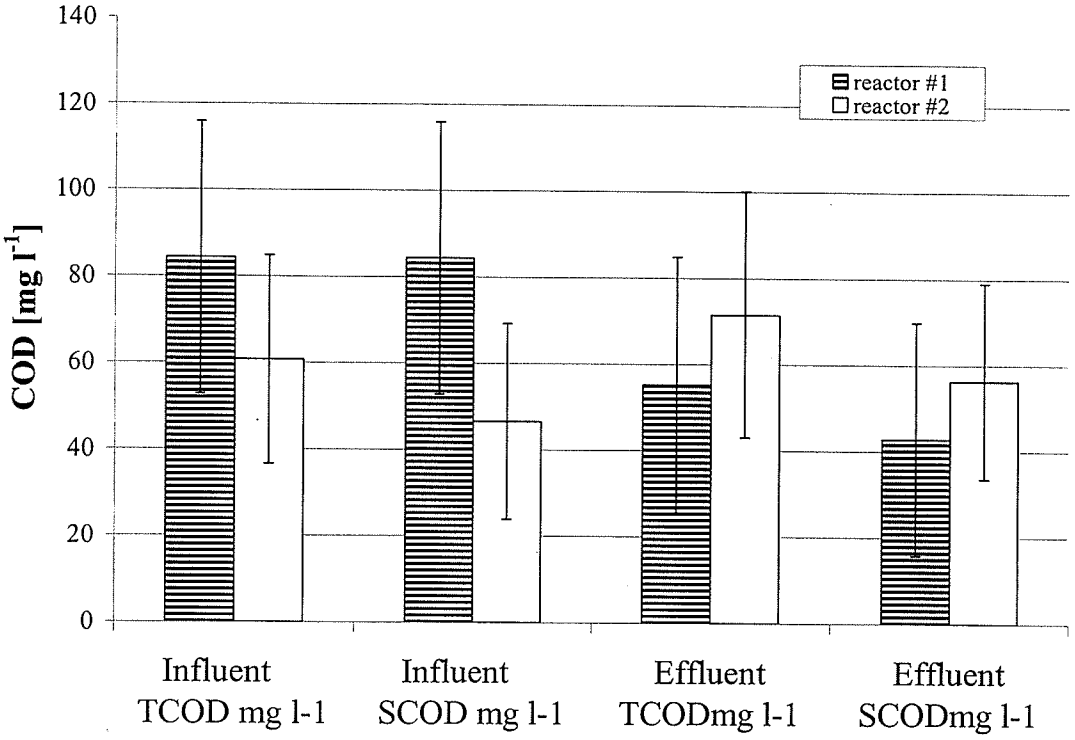


Figure 4.4 COD removal in reactor #1 and #2 (52 replicates of TCOD and SCOD in influent and effluent in each reactor)

4.3.3 Biofilm density and thickness

Changes in biofilm composition were tested over time during this laboratory study. Measurements of the total solids (TS) and volatile solids (VS) concentration within the biofilm were taken in order to determine the changes in the microorganism population and the influence of the biofilms content on its stability. Obtained results are presented in figure 4.5 (a) and 4.5 (b).

Constant, limited hydrogen supply resulted in relatively constant VS concentration equal on average to 63 gVS l^{-1} (95% CI 52 to 74 gVS l^{-1}) and 68 gVS l^{-1} (95% CI 49 to 87 gVS

l^{-1}) in reactor #1 and # 2 respectively. Despite the availability of excess nitrate no significant growth of microorganisms was observed in both of the reactors.

Larger fluctuations were observed in measured TS concentration within biofilm. Increase in TS was caused either by precipitation of the buffer components or attachments of solids present in the incoming wastewater. Obtained results showed that density of biofilm of around 400 g l^{-1} lead to limitation of substrates (possibly nitrate) transfer and following sloughing. The composition of the biofilm described by the VS/TS ratio seemed to be important for stable biofilm operation. EPS excreted by cells are gluing substances allowing creation of firm biofilm structure. Obtained results indicate that VS/TS ratio higher then 0.25 assured stable biofilm operation (Figure 4.5). Decrease of VS/TS ratio below 0.25 led to shearing of the biofilm, even for TS lower then 400 g l^{-1}.

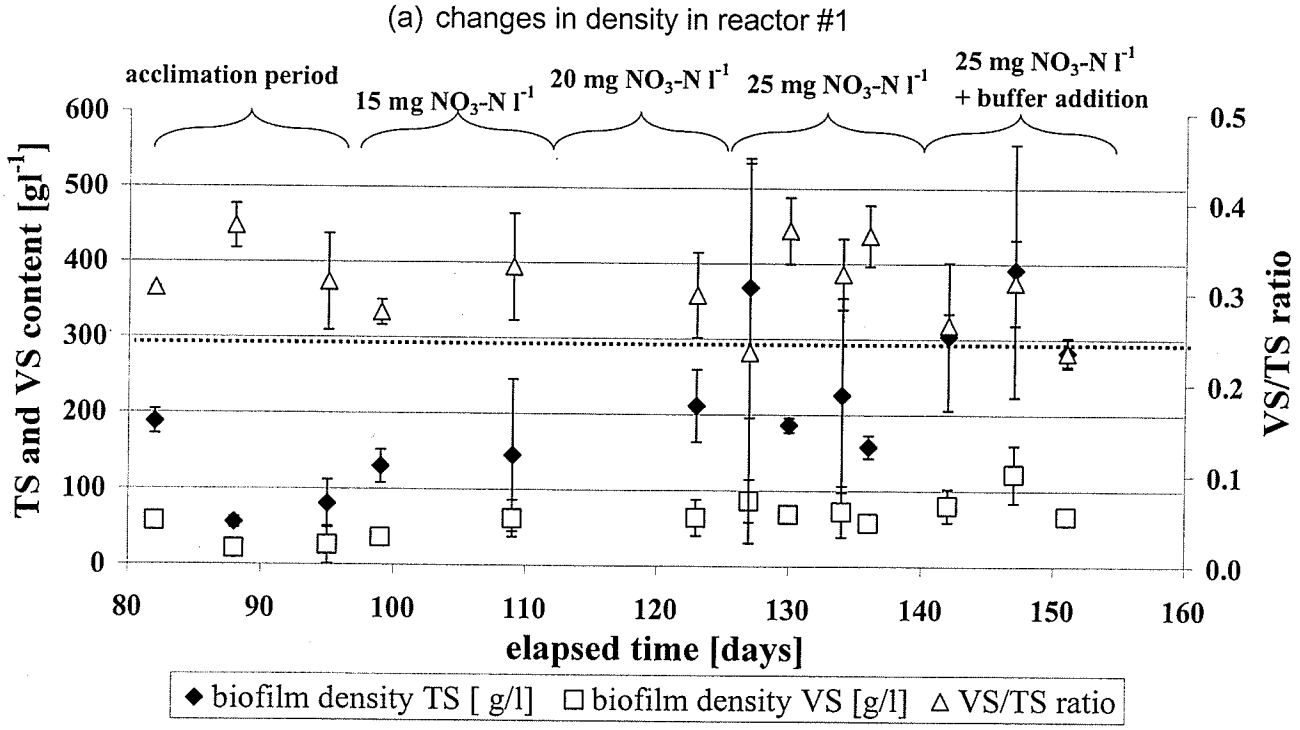
Changes in biofilm thickness during the testing period were caused by sequential precipitation of the solids from the treated bulk and sheering of the external layers of biofilm. Results showed that biofilm thickness was not the parameter responsible for stable biofilm operation. Initial operation of the relatively thick biofilm (around 500μm) was stable due to proper composition of the biofilm (VS/TS>0.25) (Figures 4.5 and 4.6). Increase in biofilm density and changes in the VS/TS ratio led to destabilizing biofilm matrix, limiting of substrate diffusion and shearing of the biofilm.

Applying increased concentrations of buffer (K_2HPO_4) for pH control (reactor #1) led to a gradual increase in total solids (TS) concentration within biofilm. The volatile solids (VS) concentration remained stable which suggested increase in inert solids such as mineral precipitants. The biofilm density increased from 158+/-15 g TS l^{-1} (95% CI 121 to 195 g TS l^{-1}) to 391 +/-167 g TS l^{-1} (95% CI 224 to 557 g TS l^{-1}) within one week of

supplying buffer (Figure 4.5 (a)). Simultaneously, increase in total suspended solids in the effluent was detected as its values raised above 20 mg TSS l^{-1}(Figure 4.3).

Application of gaseous carbon dioxide (CO_2) led to gradual decrease in inert solids concentration within biofilm. It was speculated that decrease in operational pH to pH ~ 7.0 minimized precipitations of minerals. The TS decreased from 313+/- 14 g TS l^{-1} (95% CI 278 to 348 g TS l^{-1}) to 209+/-95 g TS l^{-1} (95% CI 47 to 370 g TS l^{-1}) (Figure 4.5(b)) within one week of the reactor exposure to carbon dioxide. The total and volatile suspended solids within the effluent remained close to 10 mg l^{-1} observed through most of the experiment.

Introducing carbon dioxide in the gaseous form allowed pH control without the risk of increases the biofilm density observed when phosphates buffers substances where applied into the system.



(b) changes in density in reactor #2

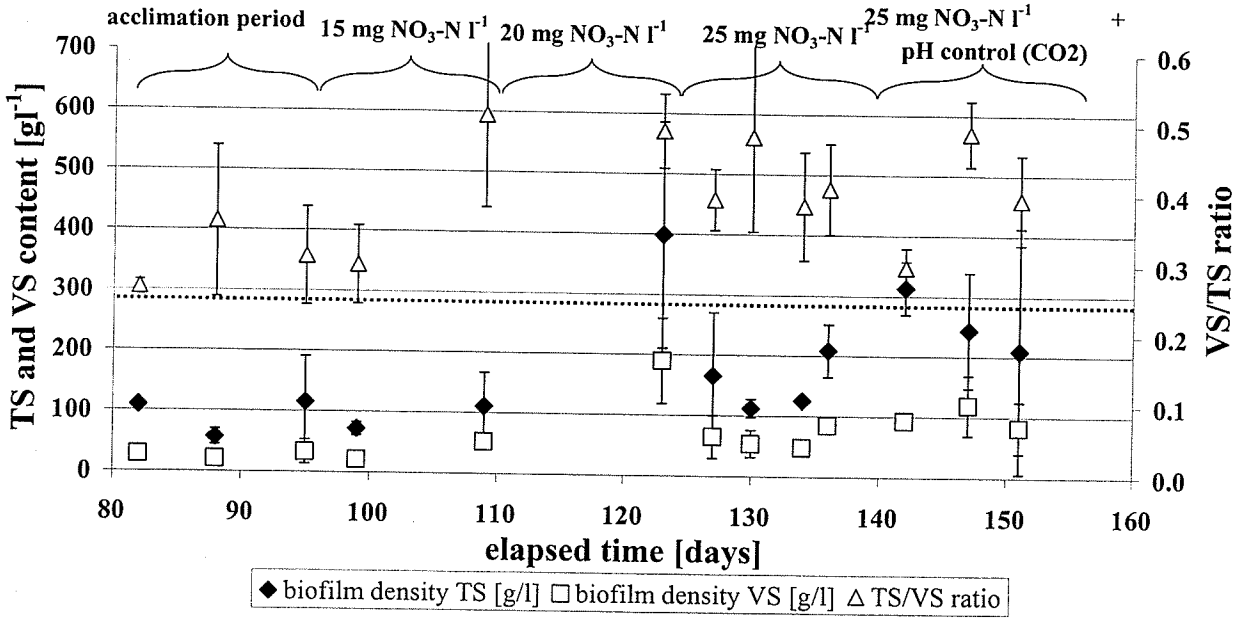


Figure 4.5 Changes in biofilm density

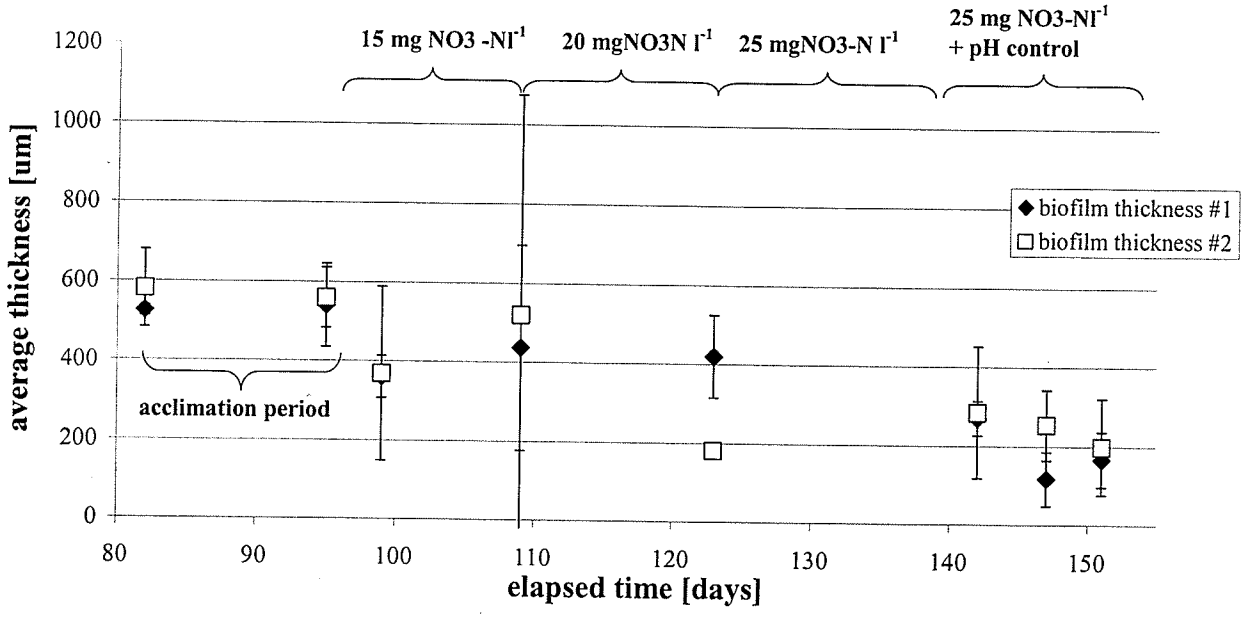


Figure 4.6 Changes in biofilm thickness

4.3.4 EPS content within a biofilm

The obtained data show that the rate of the EPS accumultion was stable. Samples were analyzed through the laboratory study together with measurements of biofilm thickness and density. No excess excretion of EPS was observed during the experiment. The averaged values obtained in the experiment are 28+/-18 mg EPS g VS^{-1} and 34+/-15 mg EPS g VS^{-1} in reactors #1 and #2 respectively. The biofilm can be then described as the one with low rate of EPS accumulation (Kreft and Wimpenny, 2002). Due to limiting growth conditions cells spend less energy on EPS synthesis and in order to survive. The created EPS are assumed not to be utilized as well in this situation. Low rate EPS production biofilms are characterized with evenly spaced bacterial cells. They are not as dense as in situation without any EPS production thus increasing biofilms porosity (Kreft and Wimpenny, 2002).

4.4 CONCLUSIONS

Membrane biofilm reactors were operated for hydrogen-driven denitrification of wastewater over a period of 152 days. During the start–up period, a biofilm developed on the membrane surface and steady-state operation was established. Limited hydrogen supply proved to be efficient for control of membrane biofilm reactor performance. Following observations were made:

1. Denitrification rates remained similar despite different types of applied wastewater (synthetic, containing biodegradable COD, SWW or municipal wastewater, MWW) or fluctuations in the substrate concentration.

2. The averaged denitrification rates were 0.50 +/- 0.02 g NO_3-N $m^{-2}d^{-1}$ for SWW and 0.59 +/- 0.04 g NO_3-N m^{-2} d^{-1} for MWW.

3. Measured COD, VSS and TSS effluent concentrations were stable and well below required values (150 mg COD l^{-1}).

4. The biofilm thickness was not as influential for stable biofilm operation as its density. Results suggest that VS/TS ratio higher then 0.25 assured stable biofilm operation. Decrease of VS/TS ratio below 0.25 led to shearing of the nonbiological outer layers of the biofilm.

5. Limited hydrogen supply assured a fairly constant volatile solids concentration.

6. The inhibitory effect of high total solids concentration was confirmed by supplying higher buffer concentrations in the influent of one reactor. This caused increased precipitation and led to 20 % decrease in denitrification rate despite operational pH of 8.4 described in literature as optimum.

Application of carbon dioxide for pH control in the second reactor caused a rapid decrease of pH (to 6.95) however the denitrification rate remained unchanged.

7. Hydrogen limitation does no allow to treat streams with fluctuating (especially increased) nitrate loading as it will result in the increased nitrate and nitrite concentrations in the effluent.

CHAPTER 5: IMPACT OF SHEAR FORCE ON THE BIOFILM STRUCTURE AND PERFORMANCE OF A MEMBRANE BIOFILM REACTOR FOR TERTIARY HYDROGEN DRIVEN DENITRIFICATION OF MUNICIPAL WASTEWATER[4]

5.1 INTRODUCTION

As mentioned in point 1.6 biofilm formation is a multi-step process to which physicochemical (diffusion force, gravity force, thermodynamic forces, opposite charge attraction, hydrophobicity, etc.) and biological (production of extracellular polymer, growth of cellular clusters, metabolic changes, etc.) forces make significant contributions. The stable three dimensional structure of the biofilm is ultimately a function of the interactive strength between aggregates and hydrodynamic shear force (Liu and Tay, 2002). The latter is extremely important as it affects mass transfer conditions, biofilm structure (thickness and density) and the extracellular polymeric substances (EPS) production. The evaluation of the shear force impact on the biofilm structure and overall efficiency of the MBfR became the basic objective of the following experiment. The specific objectives of this phase of research are described in point 5.1.4.

5.1.1 Impact of shear force caused by mixing

There is an evident relationship between hydrodynamic conditions and substrate flux in the biofilm. Mass transport of dissolved species is caused by diffusion processes. The

[4] Parts of this chapter were published *Water Research*, 2008;42(12) 3057-3065
Impact of shear force on the biofilm structure and performance of a membrane biofilm reactor for tertiary hydrogen driven denitrification
D.Celmer, J. Oleszkiewicz, N. Cicek

gradient concentration leads to creation of the concentration boundary layer close to membrane or biofilm surface. This boundary layer is called "concentration polarization layer" as shown in Figure 5.1 (Wiesner and Aptel , 1996).

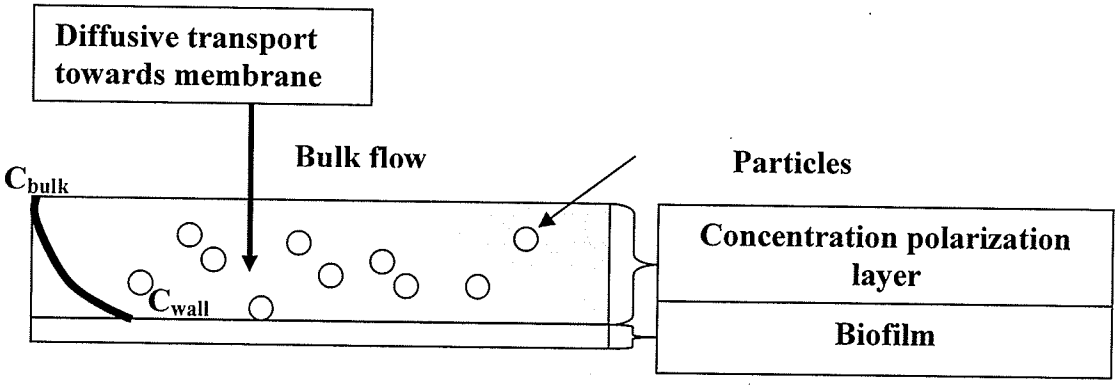


Figure 5.1 Mass transport of dissolved species and concentration polarization layer

The thickness of the concentration polarization (diffusion layer) layer is an important factor affecting the efficiency of the process. Its value can be calculated according to model developed by Dawson and Trass (1972):

$$L_B = L_0 * 0.011 * v^{-0.88} \qquad (5.1)$$

where: L_B – diffusion layer thickness[m]

L_0 – low flow diffusion layer thickness [m]

v – bulk flow velocity [m/s]

By integrating into this equation the expression of the diffusion layer thickness, one can estimate its influence on the flux:

$$J = D_b / L_B * (-\ln (c_{wall}/c_{bulk})) \qquad (5.2)$$

Where: J - solute flux;

D_b – diffusion coefficient;

L_B - concentration polarization layer thickness;

c_{wall}- pollutants concentration close to biofilm surface;

c_{bulk} – pollutants concentration in the bulk.

This model is called a film layer model and describes dissolved solids flux. The ratio of diffusivity and concentration polarization layer thickness is called the mass transfer coefficient k. The final equation is as follows (Wiesner and Aptel , 1996, Schafer, 2001)

$$J = k^* (-\ln (c_{wall}/ c_{bulk})) \quad (5.3)$$

Where: k – mass transfer coefficient

The flux is inversely proportional to the thickness of the concentration polarization layer. As expected, the higher the diffusion coefficient, the higher is the value of the flux. The increased concentration of solvents in the bulk (and lower c_{wall}/ c_{bulk} ratio) leads to increased flux.

The higher velocities of the treated stream (laminar or turbulent flow) have impact on the mass transport mechanism and finally on the substrate flux. Higher velocities result in decrease in thickness of the boundary layer and lead to higher value of flux, effecting overall membrane biofilm reactor performance.

The membrane covered with biofilm submerged in the reactor can be defined as the object that interacts with the fluid. This interaction of the membrane and the fluid can be described in terms of the forces at the liquid – body interface (Figure 5.2). This can be further described by shear stress (τ_w) due to viscous effects and normal stresses due to the pressure (p). Both τ_w and p vary in magnitude and direction along the surface. The resultant force in the direction of the upstream velocity is termed as the drag (D), while the resultant force normal to the upstream velocity is termed the lift (L). Drag (D) and lift (L) can be described by the equations 5.6 and 5.7

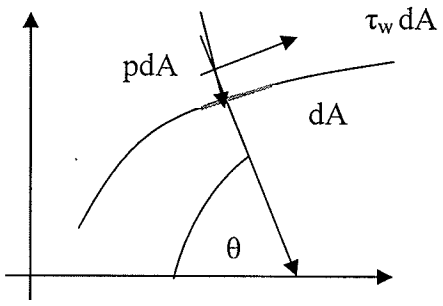


Figure 5.2 Components of the fluid force affecting the submerged body (Prasuhn A.L., 1980)

The resultant of shear stress and pressure distribution can be obtained by integrating the effect of these two quantities on the body surface. The x and y components of the fluid force on the small area element dA are:

$$dF_x = p * dA * \cos\theta + \tau_w * dA * \sin\theta \qquad (5.4)$$

and

Thus,

$$D = \int dFx = \int p \cos \Theta \, dA + \tau w \sin \Theta \, dA \qquad (5.6)$$

$$L = \int dFy = -\int p \sin \Theta \, dA + \tau w \cos \Theta \, dA \qquad (5.7)$$

The shear stress tensor still has to be related to the physical aspects of the flow. The basis for the relation is Newton's law of viscosity:

$$\tau = -\mu * \frac{dU_x}{d_y} \qquad (5.8)$$

where: μ - viscosity of the fluid

In real conditions the viscous forces will become a function of the deformation of the fluid (the velocity gradient) and the viscosity (or coefficients of viscosity), μ.

The shearing stress acting on the membrane (and thus biofilm) submerged in the reactor used during the tests is the result of the circular motion of the particles. The shear stress τ_w can be then calculated as:

$$\tau_w = F/A \qquad (5.9)$$

where: τ_w - shear stress [Nm^{-2}]

F – acting force, centripetal force [N]

A- surface area of the submerged body [m^{-2}]

As magnetic mixing involves creation of centrifugal force further calculation should be based on following equation:

$$F_{cn} = mv^2/r$$
$$F_{cn} = m * \varpi^2 * r \qquad (5.10)$$

Where: m – body mass [kg];

v – velocity [m/s];

r – radius [m];

ω – angular velocity [1/s].

The angular velocity of the particles moving in the distance equal to the stirring bar radius is equal to the angular velocity of the mixer. However the angular velocity of the particles in the vortex changes depending on the distance from the vertical axis of the

vortex. According the Helmholtz statement the changes of the angular velocity are as follows (Levi and Medina, 1995):

$$A_1 * \varpi_1 = A_2 * \omega_2$$
$$\pi * r_1^2 * \varpi_1 = \pi * r_2^2 * \varpi_2$$

As the centrifugal force values depend on the angular velocity and the radius of the particle movement, the shear stress values in the reactor will vary for different fibers – placed closer or further from the middle of the reactor. The theoretical distribution of shearing stress in the reactor is presented on the Figure 5.3. The details on calculation of theoretical shear force distribution are presented in Appendix 1.

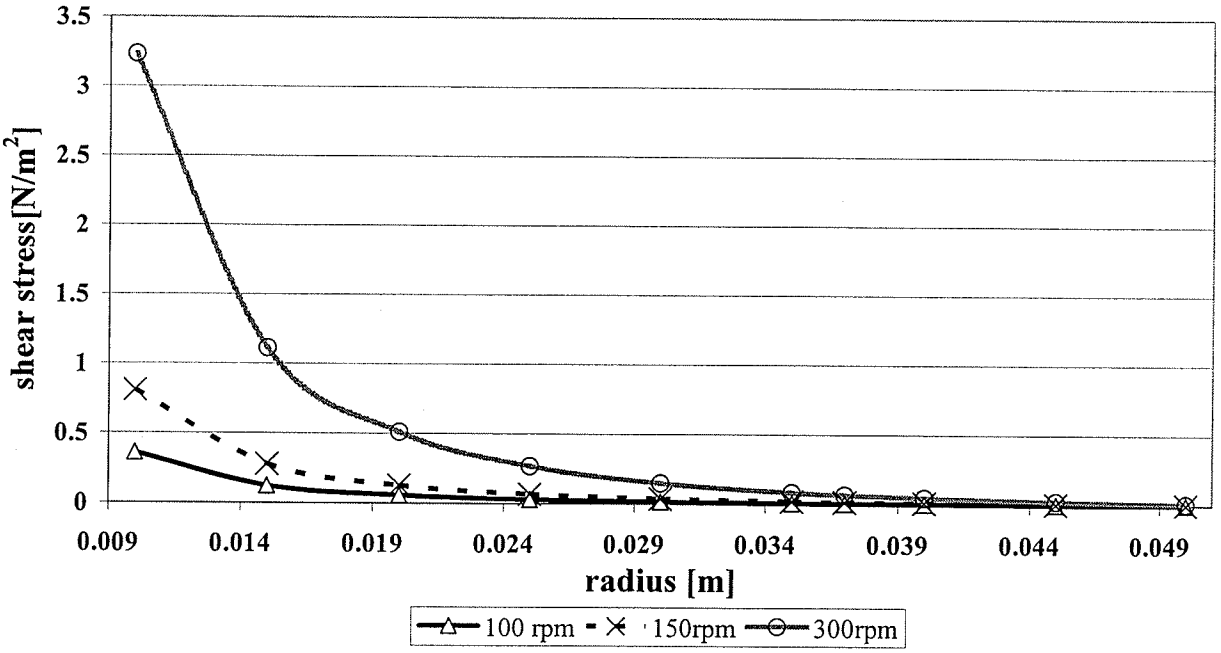


Figure 5.3 Shear stress distributions in the reactor

5.1.2 Impact of shear force caused by gas sparging

Gas sparging is another common strategy used to minimize or prevent fouling on the membrane surfaces. Some information on the gas sparging effect on confined membrane

systems (i.e. tubular membranes) has been already gathered. Impact on unconfined systems such as submerged hollow fiber membranes for gas supply (type used in this experiment) is still not clear and further studies are required.

Shear force profiles were found to be substantially affected by operating conditions i.e. gas sparging rate (i.e. gas flow rate), module configuration, fiber packing density and diffuser nozzle size (Berube et.al., 2006). Some test showed that increasing gas sparging rate increases the baseline shear signal due to increase in the bulk superficial liquid velocity. It also contributes to formation of instabilities induced by rising bubbles and creation of peak shear signals usually two to five times higher the shear force baseline. Chan et.al. (2007) observed that increasing sparging rate increases also the number of shear force events which significantly improves hydrodynamic conditions. Sparging rate is also known to affect the shape of the bubbles (spherical or ellipsoidal) and the duration of shear signal (Chan et.al., 2007). Although no significant impact of fiber packing density and diffuser nozzle size on shear force was detected, some trends were observed. Smaller diffuser nozzle and medium packing density lead to higher number of the shear events.

The wake region induced by the rising bubble and the secondary flows in the wake region play an important role in contributing to particle back- transport at the membrane surface. Other factor that affects the shear force impact of gas sparging is the location of the diffuser in the system, as well as the fiber in the membrane (outer vs. inner fibers). Generally outer fibers experience the greater amount of shear force and thus better removal of particles, when compared to the fibers located within a bundle. This limitation can be somehow overcome in the membranes with loosely held fiber bundles, where

despite overall lower shear force signal; the secondary flows generated by wake of rising bubbles cause fibers to sway. This increases the number of fibers that can benefit from gas induced shear force.

As described in previous paragraphs, determining the shear force caused by gas sparging is very complex process thus no direct measurement of shear force were carried out in this experiment. Operational conditions were based on the knowledge obtained from available publications (Berube et.al., 2006, Chan et.al., 2007) aiming at minimizing the effect of shear force and were as follows:

1. hollow fiber, hydrogen supplying membrane module was used in the experiment
2. used module configuration: membrane with loosely held fibers (should allow for more uniform impact of gas induced shear force on membrane fibers)
3. low packing density of 2 fibers/cm^2 was used (should allow for higher number on shear events)
4. diffuser: Fisherbrand Gas Diffusing Stones made of porous, fused crystalline alumina grains with average pore size of 60 μm (low diffuser nozzle size should allow for higher number on shear events)
5. sparging rate seems to impact the shear effect most significantly thus this parameter was chosen as means to verify impact of different shear force on the systems performance.

5.1.3 Impact of shear force on biofilm structure

The shear stress has a dual effect on mass transfer conditions. While high turbulence facilitates substrate diffusion into the biofilm (Point 5.1.1) it can also cause increase in

biofilm density and reduce the diffusivity of the substrate within the biofilm (Liu and Tay, 2002). This has been also observed by Beyenal and Lewandowski (2005) who demonstrated that effective diffusivity within a biofilm decreased with increase of flow velocity and increased biofilm density. There is evidence that the higher the shear force the thinner and denser the biofilm (Liu and Tay, 2002; Ohashi and Harada, 1994; Kwok et al., 1998). Also other researchers observed that biofilms created in high shear stress conditions are more compact (less porous) than those created under lower shear conditions (Livingston and Santos, 1995; Viera M.J., 1993).

Extracellular polymeric substances (EPS) are another important component of the biofilm as they impact structural integrity of the biofilm matrix (Christenses, 1989; Tsenuda et all., 2001). The type and amount of EPS determines the physicochemical properties of biofilms (Nielsen et al., 1997; Jahn and Nielsen, 1998). Microbial biopolymers are primarily composed of polysaccharides and proteins, with lipids and nucleic acids also reported. Some evidence suggests that the composition of EPS may be more important than the actual quantity of the polymer present. The composition of biopolymers is known to affect spatial organization within the biofilm due to their impact on flocculation of particulate matter and bacterial cells. Increased cell surface hydrophobicity of bacterial cultures correlate well with the adhesion of cells (Zita and Hermansson, 1997). It also affects the interactions between microbially produced substances and cations present in the treated wastewater. Examinations of the isolated polymeric substances indicate that hydrophobic fractions consist mostly of proteins not carbohydrates. Thus, it is believed that the biopolymer network is stabilized by protein - binding polysaccharides that are cross–linked to adjacent proteins (Jorand et al., 1998). The shearing force can affect EPS

accumulation due to impact on mass transfer conditions (i.e. on substrates availability) and stimulation of exopolymers production (Houghton and Quarmby, 1999; Veiga et al., 1997). It has been generally observed that high shear force leads to overproduction of EPS, mainly exopolysacharides (Ohashi and Harada, 1994; Pratt et al, 1999, Trinet et al, 1991). The optimum ratio of proteins and polysaccharides secreted by the biofilm can contribute to a balanced biofilm structure, however, the exact mechanism by which hydrodynamic shear forces stimulates the production of exopolymers is not yet clear. From a wastewater process design perspective, it is essential to create a stable biofilm, which reduces the risk of significant fluctuations with respect to effluent quality, while sustaining high removal efficiencies. Hydrodynamic shear force appears to be an effective tool for manipulating biofilm structures and controlling the membrane biofilm reactor performance.

5.1.4 Objectives

This study aimed to investigate autotrophic denitrification of low organic carbon wastewater within a biofilm growing on a hydrogen diffusing membrane. The overall objective of this experiment was to evaluate the possibility of controlling the process rates and effluent quality by manipulating biofilm characteristics using shearing stress. Varying levels of reactor mixing and nitrogen sparging were used to evaluate the impact of shearing stress on biofilm structure i.e. biofilm thickness, density, composition, EPS content.

5. 2 MATERIALS AND METHODS

5.2.1 Reactor Operation

The experimental set-up involved two laboratory-scale membrane biofilm reactors, with volumes of 3 L each. The reactors (Figure 5.4) were operated in continuous-flow mode with a hydraulic retention time of (HRT) 4 hours. The low operational HRT was chosen from the wide range of HRTs used in MBfR (from 0.5 hour to 24 hours) in order to evaluate the system under high loading. The bioreactors were seeded with a population of autotrophic denitrifiers at the first day of the operation. Hydrogen necessary for the process was delivered through the submerged fibre membrane module (GE Water & Process Technologies - ZENON Membrane Solutions). The detailed description of the membrane is presented in Table 5.1.

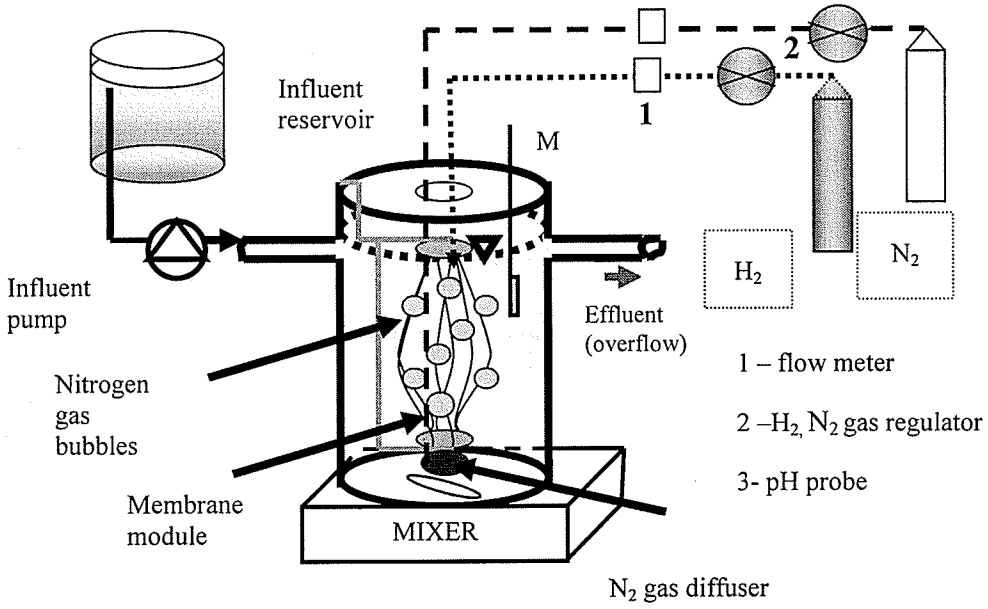


Figure 5.4 Membrane biofilm reactor set – up

Table 5.1 Description of the gas diffusing membrane

Charateristic Property	Value
	Fiber module
Manufacturer	Zenon Environmental Inc. GE Water & Process Technologies
Membrane material	polypropylen fibers
Hydrogen permeabilty	$1.34*10^{-11}$ mol/m^2/sec*m/kPa
Outer Diameter (OD) of fibers	50.9 µm
Inner Diameter (ID) of fibers	29.7 µm
Number of tows	120
Number of fibers per tow	48
Total number of fibers	5760
Fiber length	0.34 m
Membrane surface area	0.37 m^2

Constant hydrogen supply at a pressure equal to ~2.5 psi and flow of around 10 ml min^{-1} and 5 ml min^{-1} in reactor #1 and #2 was maintained throughout the experiment. This assured that hydrogen was not a limiting component according to stoichimertric demand and basing on possibility to increase denitrification rates for increased nitrogen loading. Both of the reactors were placed on magnetic stirrers, which allowed varying mixing conditions and applied shearing stress. Nitrogen (N_2) used for shearing of the excess biomass and removal of residual oxygen from the incoming wastewater was delivered through a gas diffuser submerged in the reactor.

Testing was divided into two periods: biofilm development period (period 1) and testing period (period 2) when different levels of hydrodynamic shearing stress were applied. Phase scheduling of period 2 is presented in detail in Table 5.2.

Table 5.2 Shearing stress regime

	type of applied shear stress	nitrogen flow [ml min^{-1}]	testing period [days]
phase 1	low mixing (100 rpm)	-	16
phase 2	medium mixing (150 rpm)	-	14
phase 3	high mixing (300 rpm)	-	38
phase 4	high mixing + low nitrogen spraging (low N_2 flow)	50	36
phase 5	high mixing + medium nitrogen spraging (medium N_2 flow)	150	30
phase 6	high mixing + high nitrogen spraging (high N_2 flow)	300	26

Both reactors were fed with un-disinfected final effluent collected from the City of Winnipeg-North End secondary wastewater treatment plant. Nitrates were added to the feed in the form of $NaNO_3$. The main influent wastewater parameters are presented in Table 5.3.

Table 5.3 Feed wastewater characteristics

Parameter	Units	Reactor #1	Reactor #2
SCOD	mg l^{-1}	64.63(+/-13.93)	70.01(+/-17)
NO3-N	mg l^{-1}	17.64 (+/-2.32)*	17.34(+/-2.03)*
alkalinity	mg $CaCO_3$ l^{-1}	219(+/-45)	249(+/-45)
temperature	°C	19.61(+/-2.24)	19.18(+/-1.77)
DO	mg l^{-1}	2.78(+/-1.04)	2.68(+/-1.09)
pH	-	7.09(+/-0.19)	7.02(+/-0.14)

No pH control was implemented.

* NOTE: Influent nitrate concentration was kept around 17 mg N/l during initial 4 phases. The influent concentration was increased to above 20 mg N/l in following phases in order to avoid substrate limitation.

5.2.2 Analytical Methods

Influent and effluent samples were collected daily for NO_3, NO_2, TSS and VSS analysis. Samples of influent and effluent for NO_3-N, NO_2-N and COD analysis were taken each day of the reactor operation and stored at ~ 4°C. NO_3 and NO_2 concentrations, COD concentrations as well as DO and pH, TSS and VSS values in the reactor were measured according to procedures presented in Chapter 2, points 2.3.1 and 2.3.2.

Biofilm samples for thickness and density were collected from the membrane surface. The module with biofilm was removed from the reactor for 10 min and placed in vertical position to allow excess water to drain. The samples of known surface area were removed from module with a wooden spatula and put into a 5 ml plastic syringe which was partially filled with de-ionized water and sealed. The biofilm thickness and density was determined according to procedure described in details in Chapter 2, point 2.3.3.

Carbohydrates and proteins content within the biofilm were determined using Anthrone (Viles and Silverman, 1949) and the modified Bradford method with glucose and BSA standards, respectively.

The characterization of the extracellular polymeric substances (EPS) bound within the biofilm were carried out by measuring the dry weight content (at 105 °C) of extracted EPS. The EPS were extracted in three steps: (1) addition of DOWEX MARATHON C cation exchange resin and extraction (2 h at 20°C), (2) centrifugation (10000 rpm, 10 min) and (3) acetone and ethanol precipitation (24 h at 4°C) (Comte et al., 2004). The detailed description of the EPS content determination is presented in Chapter 2, point 2.3.2.

5.3 RESULTS AND DISCUSSION

5.3.1 Impact of shear force on biofilm thickness and density

The biofilm thickness and density were a function of applied levels of shearing stress and time of exposure of the biofilm to certain hydrodynamic conditions. Different operating shearing stress regimes (see Table 5.1) resulted in different thicknesses and compositions of biofilm on the membranes. Fluctuations in biofilm structure during the testing period are presented in Figures 5.5 and 5.6. Increased levels of mixing and additional shearing resulting from gas scouring within the reactors resulted in the decrease of biofilm thickness. Increasing mixing from low to medium levels (phases 1 and 2) led to a reduction of biofilm thickness from > 1500 μm to around 700 μm. The T test comparing those two phases confirmed the significance of the change with p values equal to 0.006 and 0.032 for reactor #1 and reactor #2, respectively. Further increase in the applied shearing stress through increased mixing (phase 3) did not result in significant changes in biofilm thickness. However, introduction of nitrogen scouring resulted in a further reduction of the biofilm thickness. Thickness observed for the highest applied shear force was equal to 324+/-75 μm (95% CI 276 to 348μm) and 267+/-121 μm (95% CI 205-347μm) in reactors #1 and #2, respectively. The comparison of phase with the lowest highest applied shear force (phase 1 vs phase 6) show significant difference with p= 0.01 and p=0.0004 in reactors 1 and 2 respectively. The detailed results of statistical analysis of thickness in following phases are presented on the Figure 5.5.

Changes of biofilm thickness with gradually increasing shear force (Figure 5.5) manifest themselves in detachment of biofilm layers (Figure 5.6). Despite the lowest applied shear force in the initial phase of the study, a significant portion of the biofilm was removed.

Further increase in applied shear force resulted in less significant changes in biofilm thickness. These results confirm observations of other researchers (Coufort et al., 2007), who reported that the biofilm consisted of distinct layers. The top layer of the biofilm was very fragile and could be easily detached while the middle and basal layers were characterized by intermediate to high cohesion and high shear stress resistance.

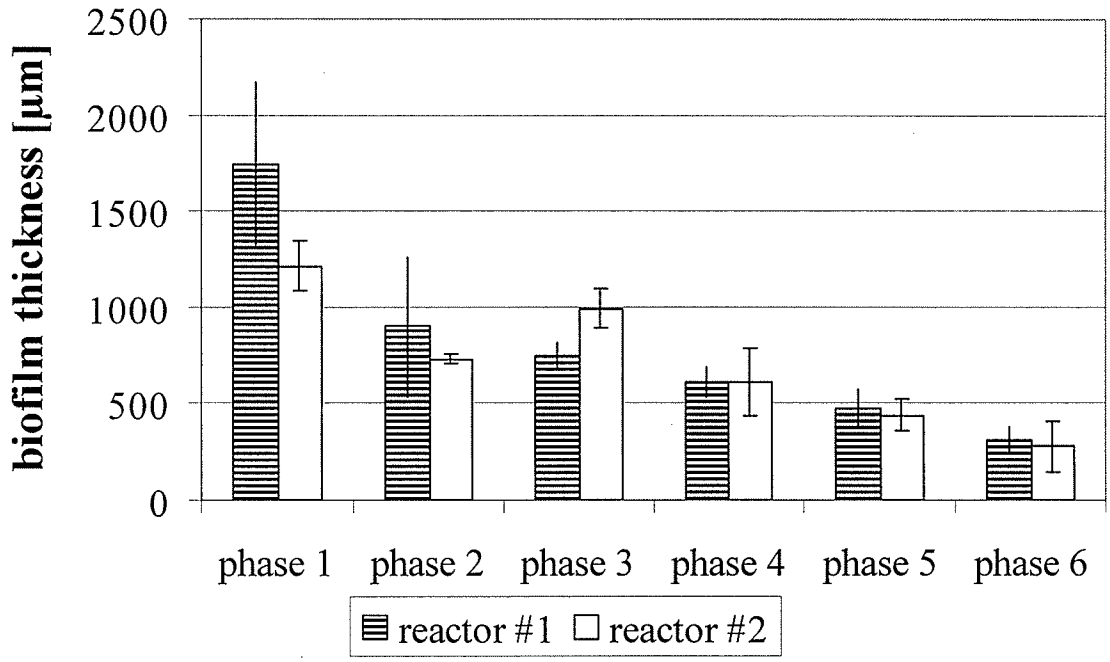


Figure 5.5 Changes in biofilm thickness for varying applied shearing force (from 10 -25 duplicated per phase). *Phase1- low mixing; phase 2- medium mixing; phase 3-high mixing; phase 4- high mixing+ low N_2 sparging; phase 5- high mixing+ medium N_2 sparging; phase 6- high mixing+ high N_2 sparging*

p values for reactor 1

phase 1vs2	*phase 2vs3*	*phase 3vs4*	*phase 4vs5*	*phase 5vs6*
0.006	*0.438*	*0.218*	*0.494*	*0.121*

p values for reactor 2

phase 1vs2	*phase 2vs3*	*phase 3vs4*	*phase 4vs5*	*phase 5vs6*
0.032	*0.119*	*0.015*	*0.058*	*0.170*

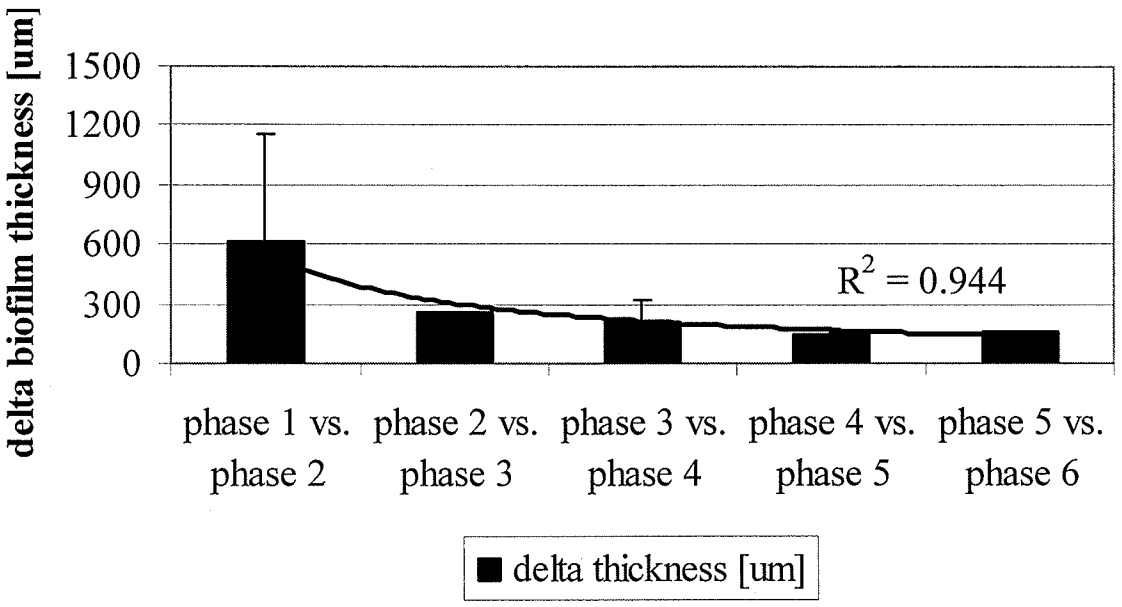


Figure 5.6 Δ biofilm thickness between experimental phases

The results of simultaneous measurements of biofilm density are shown on Figure 5.7 (a) and 5.7(b). The average values seem to suggest that together with increased shearing force and decrease in biofilm thickness, biofilm density increases. However due to the high standard deviation in the measurements, statistical analysis of data showed no significant changes in total and volatile solids content in the biofilm during all phases ($p > 0.05$). The total solids concentration was equal to 77 +/-21 g l^{-1} and 78+/-27 g l^{-1} in reactors #1 and #2 respectively. Volatile solids content was equal to 50+/-11 g l^{-1} and 53+/-15 g l^{-1} in two tested reactors.

The correlation between biofilm thickness and VS/TS ratio is presented on Figure 5.7(c). No significant trend in VS/TS ratio was observed with increased shear stress and corresponding reduction in biofilm thickness. The VS/TS ratio was stable and equal to 0.67+/-0.04 and 0.69+/-0.06 in both tested reactors. The overall composition of the

biofilm as described by the VS/TS ratio is known to be important for stable biofilm operation. EPS excreted by cells have adhesive qualities, allowing for the creation of a firm biofilm structure. Previously obtained results (Celmer et al. 2006) indicate that biofilms carrying out hydrogenotrophic denitrification can contain high content of inert solids and that a VS/TS ratio higher than 0.25 needs to be maintained to assure stable biofilm operation and prevent biofilm sloughing.

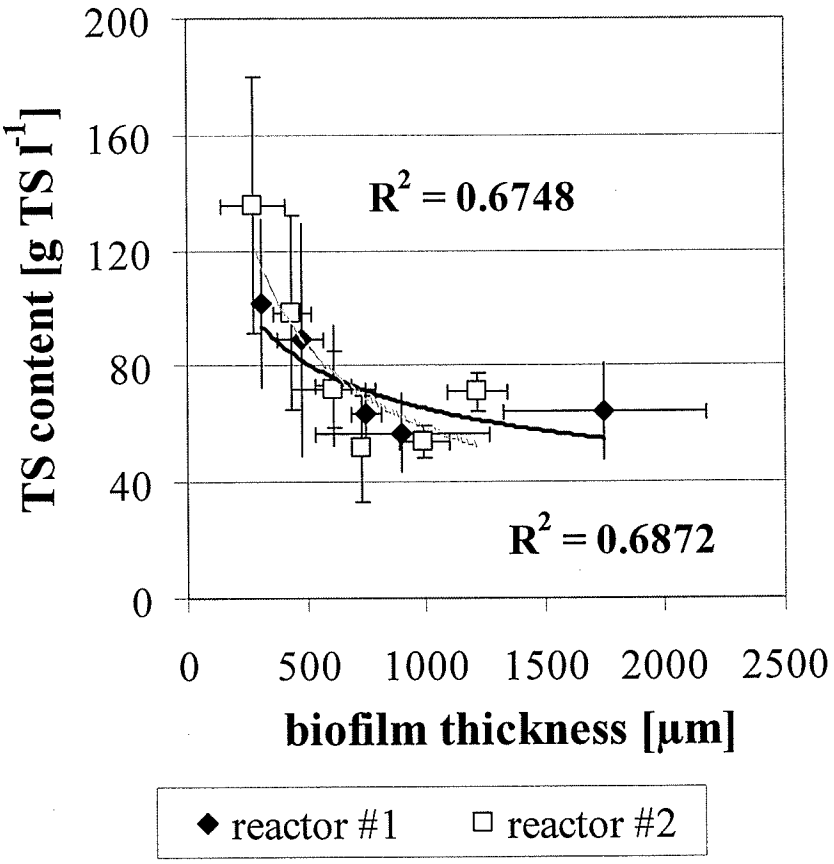


Figure 5.7(a) Fluctuations in biofilm density and VS/TS ratio for different shearing stress regimes and biofilm thickness **((a) total solids)** (from 15-25 replicates per each phase)

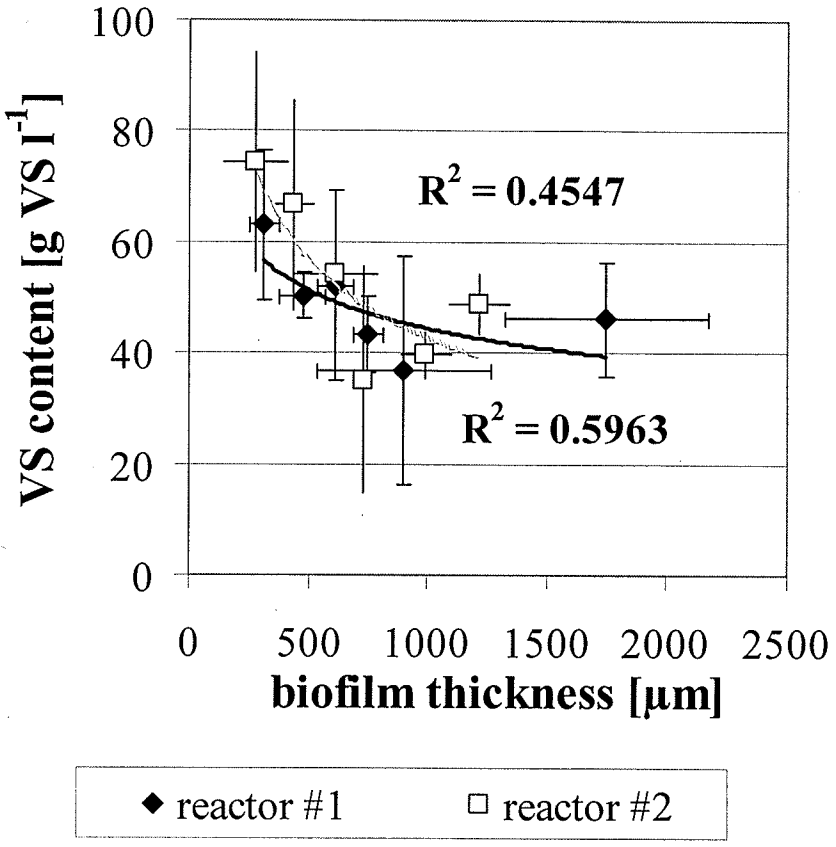


Figure 5.7(b) Fluctuations in biofilm density and VS/TS ratio for different shearing stress regimes and biofilm thickness **((b) volatile solids)**(from 15-25 replicates per each phase)

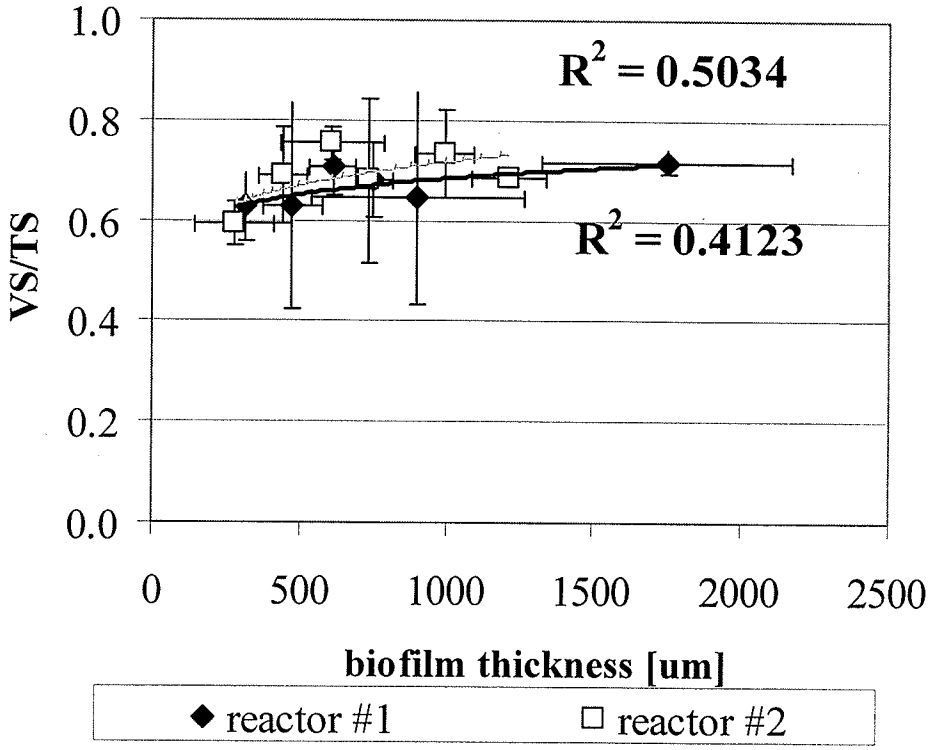


Figure 5.7(c) Fluctuations in biofilm density and VS/TS ratio for different shearing stress regimes and biofilm thickness **((c) vs/ts ratio)**

5. 3.2 Impact of biofilm thickness on EPS accumulation

Data presented in Figure 5.8 show the relationship between biofilm thickness and EPS accumulation per volatile solids concentration. As mentioned in the previous paragraph, increased levels of shearing stress resulted in the reduction of biofilm thickness. Simultaneous measurements of EPS concentration in the biofilm showed some correlation between biofilm thickness and EPS content. Results suggest that thin biofilms were characterized by low EPS content equal to ~ 40 mg EPS (g VS)$^{-1}$. Reduction in biofilm thickness from ~ 1200 μm to ~ 500 μm led to a decline in EPS content from ~ 150 mg EPS (g VS)$^{-1}$ to around 40 mg EPS (g VS)$^{-1}$ possibly due to

reduced entrapment of excreted polymers in the biofilm matrix. When biofilm thickness reached ~1700 μm during low shear force periods, however, EPS decreased to ~ 30 mg EPS (g VS)$^{-1}$, which could have been caused by EPS utilization due to creation of substrate limited conditions (starvation conditions) in deeper layers of the biofilm. Further research with thick biofilms would be required to confirm this observation.

Figure 5.8 shows the trend and the relatively high EPS variability expressed as standard deviation, which was attributed to fluctuations in biofilm morphology and composition along the membrane fiber.

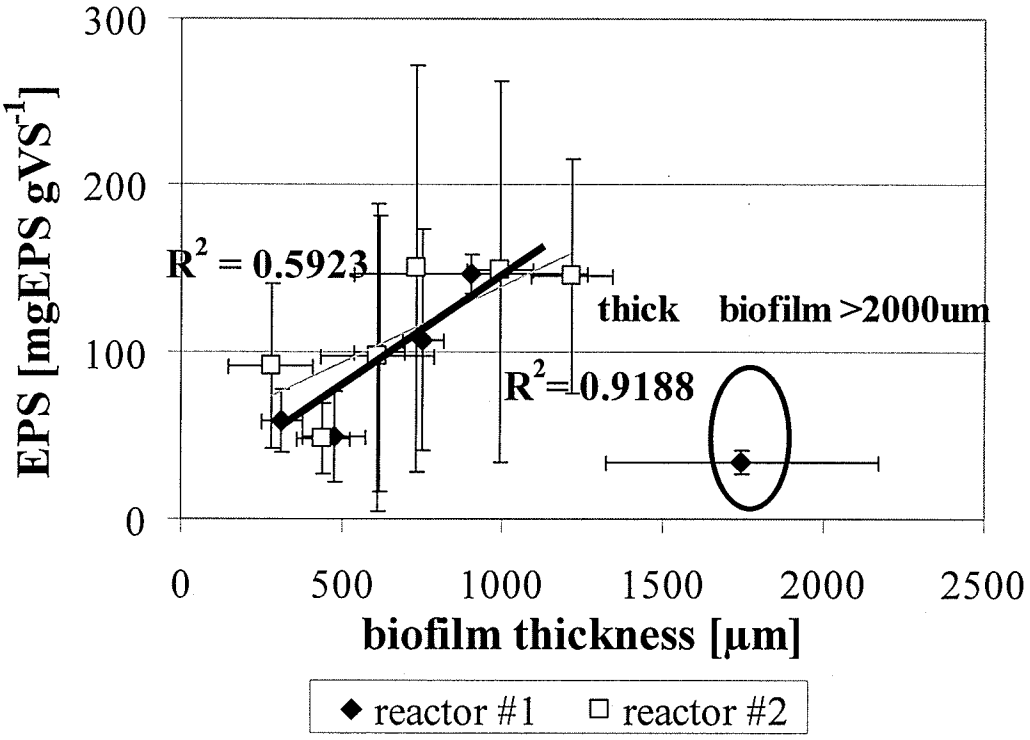


Figure 5.8 Effect of biofilm thickness on EPS [mg EPS/g VS] content within biofilm (from 15-25 replicates per each phase)

5.3.3 Impact of biofilm structure on carbohydrates and protein in the biofilm

Although carbohydrates have often been regarded as the most important extracellular components (Christensen, 1989), proteins were found at relatively higher levels than

carbohydrates in the biofilm during this study. Protein concentrations varied from 51mg proteins (g VS)$^{-1}$ to 279 mg proteins (g VS)$^{-1}$, while concentrations of carbohydrates varied from 7 mg carbohydrates (g VS)$^{-1}$ to 149 mg carbohydrates (g VS)$^{-1}$. This observation is consistent with work by Jahn and Nielsen (1998) who also observed that proteins and humic substances were the main components of biofilms. The calculated carbohydrates to proteins ratio (c/p ratio) varied from 0.1 to 0.8, which is also comparable to the results obtained by Jahn and Nielsen who analyzed sewer biofilms and observed c/p between 0.25-0.6.

However contrary to previous research, where higher shear force led to overproduction of carbohydrates (Ohashi and Harada, 1994; Pratt et al, 1999; Trinet et al, 1991), the results of this study did not show any significant correlation between protein (p), carbohydrates (c), and carbohydrates to protein ratio (c/p) and shear stress. The protein and carbohydrates content in the biofilm was related to biofilm density (i.e. the total and volatile solids concentration). The obtained relationship between biofilm density (VS and TS) and c/p ratio is presented on Figure 5.9 (a) and (b) respectively. Increase in volatile solids content from 50+/-8 (95% CI 32 to 68 g VS l^{-1}) to 94+/-7 g VS l^{-1} (95% CI 78 to 110 g VS l^{-1}) resulted in an increase in measured protein content from 25+/-4 (95% CI 16 to 34 mg (g VS)$^{-1}$) to 198+/-43 mg (g VS)$^{-1}$ (95% CI 101 to 294 mg (g VS)$^{-1}$). Contrary, content of carbohydrates seemed to decrease together with increase in total and volatile solids content. The increase of total solids content from 70+/-23 g TS l^{-1} (95% CI 18 to 122 g VS l^{-1}) to 147+/-20 g TS l^{-1} (95% CI 116 to 177 g VS l^{-1}) corresponded to a decrease in carbohydrates concentration from 74+/-29 (95% CI 10 to 137 mg (g VS)$^{-1}$) to 13+/-8 mg carbohydrates (g VS)$^{-1}$(95% CI 1 to 25 mg (g VS)$^{-1}$).

The obtained results suggest that the denser biofilm was characterized with higher protein content while a decrease in biofilm density lead to an additional accumulation of carbohydrates. Consequently, increases in biofilm density lead to lower measured c/p ratio. It has been speculated that an increase in biofilm density leads to decrease in food to microorganism ratio (F/M ratio), which has been reported as one reason for lower carbohydrates accumulation (Liao et al., 2001).

It is believed that proteins provide most of the binding sites within a biofilm (Higgins and Novak, 1997; Houghton and Quambry, 1999) as its hydrophobic coat increases attachment capacities. Conditioning layers produced by proteins create different types of bonds with polysaccharides and thus produce polymers, which are known to have affinity to minerals such as carbonates and phosphates. Thus, denser biofilms with lower c/p ratio should be more stable and reduce the risk of biomass sloughing and VSS or COD breakthrough in the effluent.

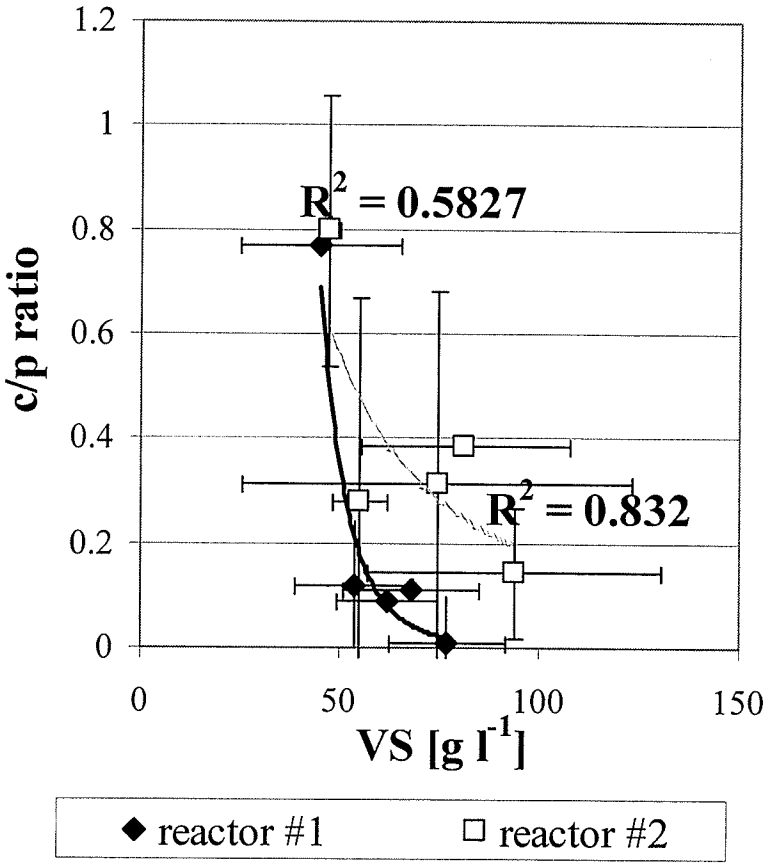


Figure 5.9 (a) Correlation between VS (a) and c/p ratio in the biofilm (from 15-25 replicates per each phase)

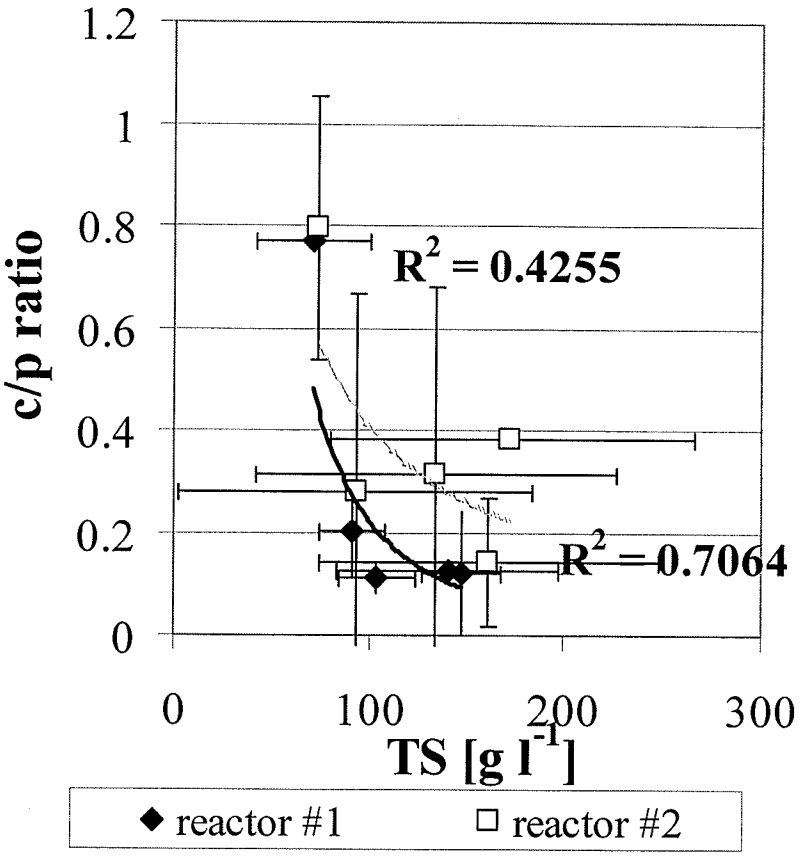


Figure 5.9 (b) Correlation between TS (b) and c/p ratio in the biofilm (from 15-25 replicates per each phase)

5.3.4 Impact of shear force on denitrification rates

Denitrification rates obtained for different shearing stress regimes are presented in Figure 5.10. Increased levels of hydrodynamic shearing force and additional shearing resulting from nitrogen sparging within the reactors led to improved denitrification rates. Average removal rates observed for low shear force and biofilm thickness of 1748 μm (95% CI 1357 to 2139 μm) (reactor #1) and 1215 μm (95% CI 1108 to 1320 μm) (reactor #2) were equal to 0.40 +/- 0.18 (95% CI 0.24 to 0.50) g NO_3-N $m^{-2}d^{-1}$ and 0.51+/-0.14 (95% CI 0.43 to 0.59) g NO_3-N $m^{-2}d^{-1}$ respectively. Increase of shearing stress, which led to a

two-fold decrease in biofilm thickness (from > 1500 um to around 800 μm in reactor #1), resulted in approximately 60% increase in denitrification rates to 0.63+/- 0.11 (95% CI 0.57 to 0.69) g NO_3-N $m^{-2}d^{-1}$ in reactor #1. Changes in observed average nitrate removal rate in reactor #2 were not as significant and removal increased by only 15% from 0.51+/-0.14 to 0.58 +/- 0.09 (95% CI 0.53 to 0.63) g g NO_3-N $m^{-2}d^{-1}$, when biofilm thickness decreased from 1215μm (95% CI 1108 to 1320 μm) to around 730 μm (95% CI 712 to 750 μm). This observation suggests that exceeding 1200 μm of biofilm thickness severely impacted mass transfer conditions and limited denitrification rates.

When sparging with nitrogen was introduced as an additional source of shearing stress, further improvements in nitrate removal rates were observed. During phase 4, biofilm thicknesses decreased to around 630 μm and removal rates reached the maximum possible at the applied nitrate loading (0.62 +/- 0.1 g NO_3-N $m^{-2}d^{-1}$; 95% CI 0.58 to 0.66 g NO_3-N $m^{-2}d^{-1}$) in both of the reactors. Further increasing of shearing stress combined with increased nitrate loading (applied to the system in order to avoid substrate limited conditions) led to additional improvement in denitrification rates. Denitrification rates determined in phase 6 were on the average equal to 0.93 +/- 0.14 g NO_3-N $m^{-2}d^{-1}$ (95 % CI 0.88 to 0.98 g NO_3-N $m^{-2}d^{-1}$) and 0.88 +/- 0.09 g NO_3-N $m^{-2}d^{-1}$ (95%CI 0.86 to 0.92 g NO_3-N $m^{-2}d^{-1}$)in reactor #1 and #2, respectively. A t-test conducted on the data shows significant difference between phase 1 and phase 6 ($p= 1.8*10^{-16}$ and $p= 5.3*10^{-16}$ for reactor 1 and 2 respectively), indicating that shear force can be used to control removal rates. The details on statistical analysis of removal rates in 6 tested phases (presented on Figure 5.10) confirms the beficiary impact of mixing and nitrogen sparging on denitrification efficiency.

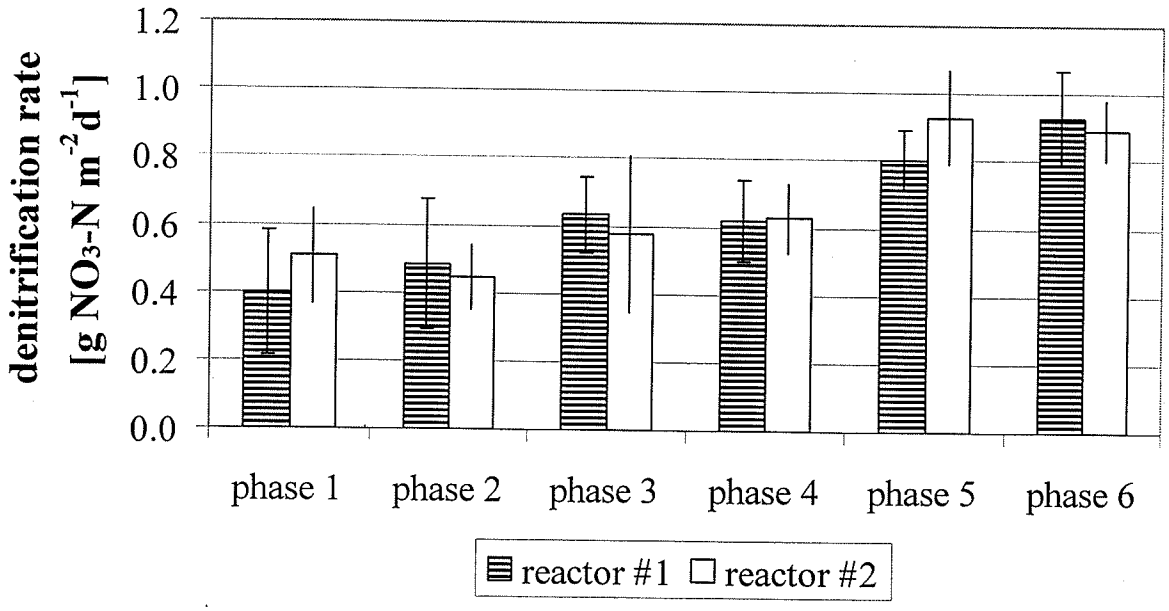


Figure 5.10 Denitrification rates obtained for different shearing stress regimes (from 25-31 duplicates per phase). *Phase1- low mixing; phase 2- medium mixing; phase 3-high mixing; phase 4- high mixing+ low N_2 sparging; phase 5- high mixing+ medium N_2 sparging; phase 6- high mixing+ high N_2 sparging*

p values for reactor 1

phase 1vs2	*phase 2vs3*	*phase 3vs4*	*phase 4vs5*	*phase 5vs6*
0.00600	*0.00006*	*0.69145*	*$2.49*10^{-9}$*	*0.00010*

p values for reactor 2

phase 1vs2	*phase 2vs3*	*phase 3vs4*	*phase 4vs5*	*phase 5vs6*
0.03200	*0.00165*	*0.09799*	*$7.43*10^{-14}$*	*0.19541*

5.3.5 Correlation between denitrification rates and biofilm thickness

The impact of biofilm thickness on denitrification rates seemed to be more significant than its density. Figure 5.11 shows the correlation between biofilm thicknesses and denitrification rates obtained in each of the phases. The relationship between biofilm

thickness and denitrification rate was well described by the power function. The correlation coefficients were equal to R^2= 0.8331 and R^2= 0.8475 in reactors #1 and #2 respectively.

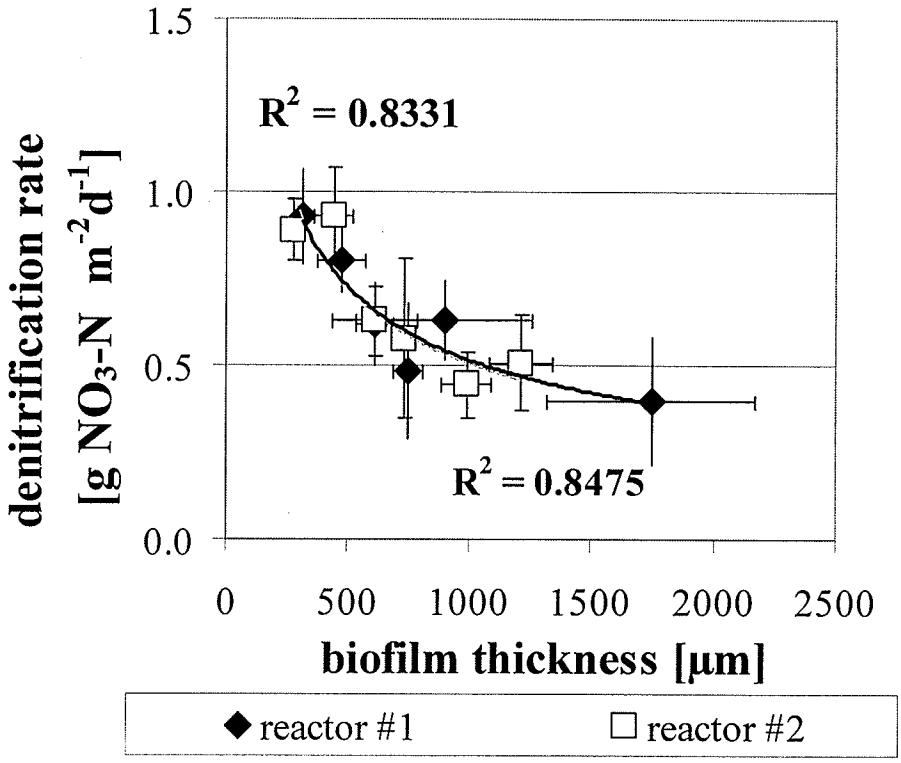


Figure 5.11 Correlation between biofilm thickness and denitrification rate

5.3.6 Impact of EPS content and protein, carbohydrates content on denitrification rates

Results show that removal efficiency increased with decreasing biofilm thickness and decreasing EPS accumulation in the biofilm. The correlation between EPS content and denitrification rates is presented on Figure 5.12 (a). Decrease in average EPS content from 116+/-21 mg EPS (g VS)$^{-1}$ (95% CI 94 to 138 mg EPS (g VS)$^{-1}$) to 37+/-9 mg EPS

(g VS)$^{-1}$ (95% CI 23 to 51 mg EPS (g VS)$^{-1}$) related to increase of denitrification rate from 0.51+/-0.14 g NO_3-N $m^{-2}d^{-1}$ to 0.97 +/- 0.13 g NO_3-N $m^{-2}d^{-1}$ (reactor #2). A similar trend was observed in reactor #1 when EPS content decreased from 103+/- 46 (95% CI 60 to 145.5 mg EPS (g VS)$^{-1}$) to 49+/-26 mg EPS (g VS)$^{-1}$ (95% CI 27 to 72 mg EPS (g VS)$^{-1}$) and denitrification rate increased from 0.48+/-0.19 g NO_3-N $m^{-2}d^{-1}$ to 0.80+/-0.10 g NO_3-N $m^{-2}d^{-1}$. Previous researchers showed that increases of bacterial EPS promote the accumulation of bacteria on the membrane surface and increases biofilm resistance (Ye et al., 2005) thus lower EPS should facilitate substrate diffusion and improve denitrification rates.

Contrary, significant increase in biofilm thickness (>1700μm) observed during the low shear force regime in reactor #1 led to the creation of a biofilm with low EPS content. Removal rates obtained for this part of experiment was relatively low and equal to 0.40 +/-0.18 g NO_3-N $m^{-2}d^{-1}$ while EPS content was equal to 32+/-4 mg EPS (g VS)$^{-1}$ (95% CI 27 to 37 mg EPS (g VS)$^{-1}$) . It was speculated that substrate availability was limited due to increased resistance of the thick biofilm and that the change in the EPS accumulation was related to simultaneous decrease in food to microorganism ratio, which has been previously described as an important factor affecting EPS accumulation (Laspidou, 2003; Celmer et al. 2006).

The content of proteins and carbohydrates has so far been shown as important for flocculation and stability of the biofilm (Houghton and Quambry, 1999; Higgins and Novak, 1997). In this study, there was medium correlation between the c/p ratio and observed denitrification rate (Figure 5.12 (b)). Both reactors exhibited similar trends where the denitrification rate was inversely proportional to c/p. Decrease in calculated c/p

from 0.79+/-0.07 to 0.14+/-0.12 resulted in increase of observed denitrification rate from 0.73 g NO_3-N $m^{-2}d^{-1}$ to 0.96 g NO_3-N $m^{-2}d^{-1}$ (reactor #1), while minimal calculated c/p ratio equal to 0.01+/-0.01 corresponded to denitrification rate equal to 1.04 g NO_3-N $m^{-2}d^{-1}$ (reactor #2). Low c/p ratio seems to be advantageous to both stability and efficiency of the membrane biofilm reactor. The capsule that is created around the bacteria, which is composed mostly of the complex carbohydrates, plays number of roles such as keeping bacterium from drying out and protecting it from phagocytosis (engulfing), while also acting as a selective diffusion medium. Decrease of carbohydrates content within the EPS matrix suggests minimization of this EPS capsule, which was shown to minimize the time of solute permeation (Freire- Nordi et.al., 2006). Faster diffusion of substrate through EPS matrix should allow for higher removal rates.

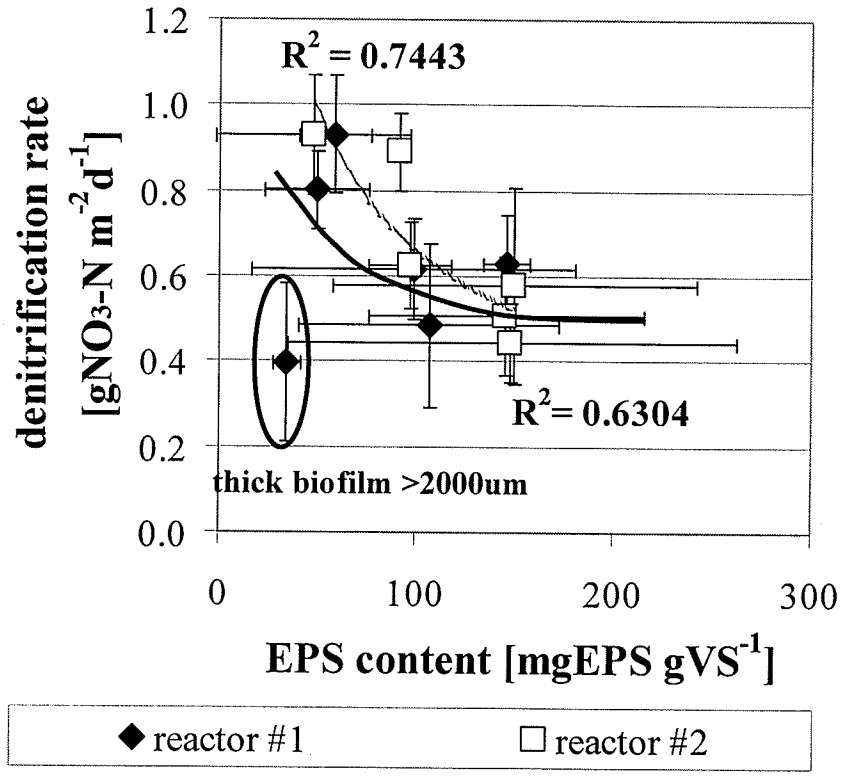


Figure 5.12 (a) Correlation between EPS content [mg EPS gVS^{-1}] and denitrification rates (from 15-25 of EPS measurments)

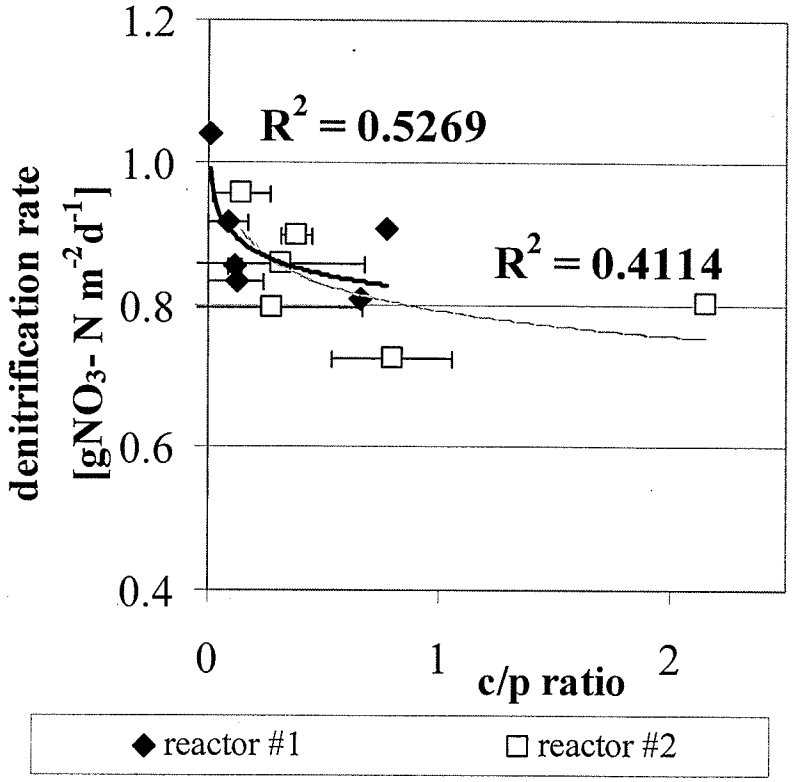


Figure 5.12(b) Correlation between c/p and denitrification rates

5.3.7 Relative efficiency of gas sparging vs. mixing

Both of the tested methods, mixing and gas sparging, showed to be efficient in improving denitrification rates due to changing biofilm structure and improving hydrodynamic conditions. No significant differences in the effectiveness of applying shear force by mixing or gas sparging were observed. Increasing mixing and nitrogen flow by 200% allowed an increase in denitrification rates by 36+/-32% and 39+/-12 respectively. Applying nitrogen sparging into a denitrifying MBfR could be a feasible option, as reactor head-space gas, rich in nitrogen from the denitrification process, can be recycled within the system for this use.

5.3.8 TSS, VSS and COD in the effluent

Successful application of the tested membrane biofilm reactor for polishing final effluent depends also on the COD, TSS and VSS concentrations in the effluent, particularly if this is the last treatment step and there is no post-filtration.

After initial detachment of biomass due to the sudden change of hydrodynamic conditions (between testing phases) effluent solids stabilized at levels consistently below 20 mg l^{-1}, which is lower then the adopted discharge from wastewater treatment plants limit of 30 mg TS l^{-1}.

Similar trends were observed in both reactors. Lower shearing stress (phase 1, 2) resulted in solids accumulation at the biofilm surface and on the average effluent concentrations were lower than values measured in the influent. The influent concentrations measured for the lowest applied shear force were equal to 33 +/-6 mg TSS l^{-1} and 20+/-4 mg VSS l^{-1} while effluent values were only 11 mg TSS l^{-1} and 7 mg VSS l^{-1}. Higher shearing stress (phases 3, 4, 5, 6) limited this process, additionally causing shearing of the biofilm surfaces. As a result, effluent values were equal to 17+/-8 mg TSS l^{-1} and 15+/-7 mg VSS l^{-1}, while influent total and volatile suspended solids were equal to only 6+/-2 mg TSS l^{-1} and 5+/-2 mg VSS l^{-1}.

Total and soluble COD breakthrough in the effluent, which is affected by VSS concentration and the excreted soluble EPS, is one of the main concerns for membrane biofilm reactors. Sudden increases in effluent total COD were observed due to detachment of biomass at the onset of each higher shear regime. During biomass detachment the total effluent COD increased up to 120 +/-1.5 mg l^{-1} in reactor #1 and 190+/-20 mg l^{-1} in reactor # 2. However no significant changes in the average influent

and effluent total and soluble COD during steady state conditions were observed. The tests showed that the wastewater used during the experiment contained negligible biodegradable COD, thus no significant removal was observed. The values measured in the effluent during steady state conditions were in the range of 60-80 mg COD l^{-1} which is below local discharge requirements of 150 mg l^{-1}(Table 5.4)

Table 5.4 Influent and effluent COD concentrations during 6 phases of the experiment

		TCOD		SCOD	
		influent	effluent	influent	effluent
phase 1	reactor #1	71+/-27	67+/-11	56+/-16	61+/-2
	reactor #2	78+/-34	67+/-27	50+/-19	56+/-19
phase 2	reactor #1	63+/-18	69+/-17	52+/-14	57+/-7
	reactor #2	63+/-13	102+/-34	58+/-12	60+/-8
phase 3	reactor #1	72+/-15	68+/-17	64+/-11	60+/-12
	reactor #2	76+/-21	80+/-17	71+/-16	69+/-17
phase 4	reactor #1	61+/-15	71+/-21	65+/-17	61+/-7
	reactor #2	53+/-21	99+/-42	64+/-10	68+/-13
phase 5	reactor #1	61+/-7	63+/-2	61+/-9	58+/-7
	reactor #2	62+/-5	100+/-54	58.+/-7	60+/-10
phase 6	reactor #1	53+/-6	65+/-19	56+/-10	51+/6
	reactor #2	43+/-7	63+/-14	51+/-5	51+/-5

5.3.9 Hydrogen utilization efficiency

Hydrogen utilization is important parameter which can be decisive for efficiency and economical feasibility of MBfR for hydrogenotrophic denitrification. Hydrogen is one of the least soluble gases and easily evaporates to the atmosphere thus efficiency of its utilization is one of the main concerns. The hydrogen utilization efficiency (HUE) was obtained from denitrification stoichiometry and varied between 40% and 100% and it increased with increasing shear force. The HUE calculations were impossible to make for

higher shear force (phases 4, 5, 6) for reactor #2 as the hydrogen flow became to low to detect by the used flowmeter. No data are provided for these phases however the suspected HUE was most likely around ~ 100% as high removal rates were still observed. The results are presented on Figure 5.13.

Observed HUE was higher when comparing to values presented by other researchers, which stated HUE close to 40- 50% (Ergas and Reuss, 2001; Terada et al., 2006) which suggests that hollow fiber, diffusive membrane combined with shear force based methods allows for high HUE. The results suggest that hydrogen utilization efficiency increased together with decrease in biofilm thickness and simultaneous increase in biofilm density. A power relationship is presented on Figure 5.14

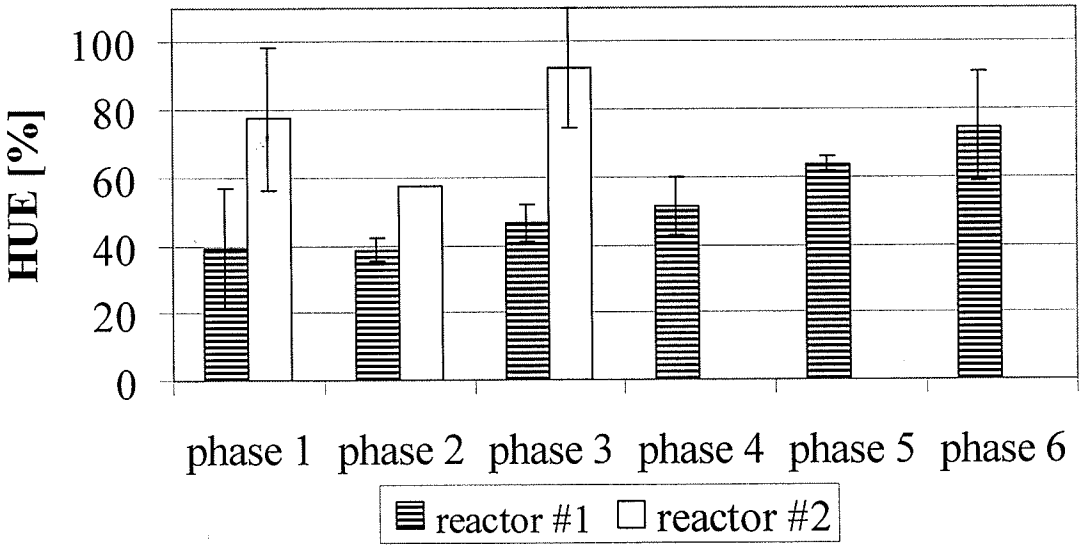


Figure 5.13 Hydrogen utilization efficiency (HUE) for shear force phases (from 25-31 duplicates per phase). *Phase1- low mixing; phase 2- medium mixing; phase 3-high mixing; phase 4- high mixing+ low N_2 sparging; phase 5- high mixing+ medium N_2 sparging; phase 6- high mixing+ high N_2 sparging*

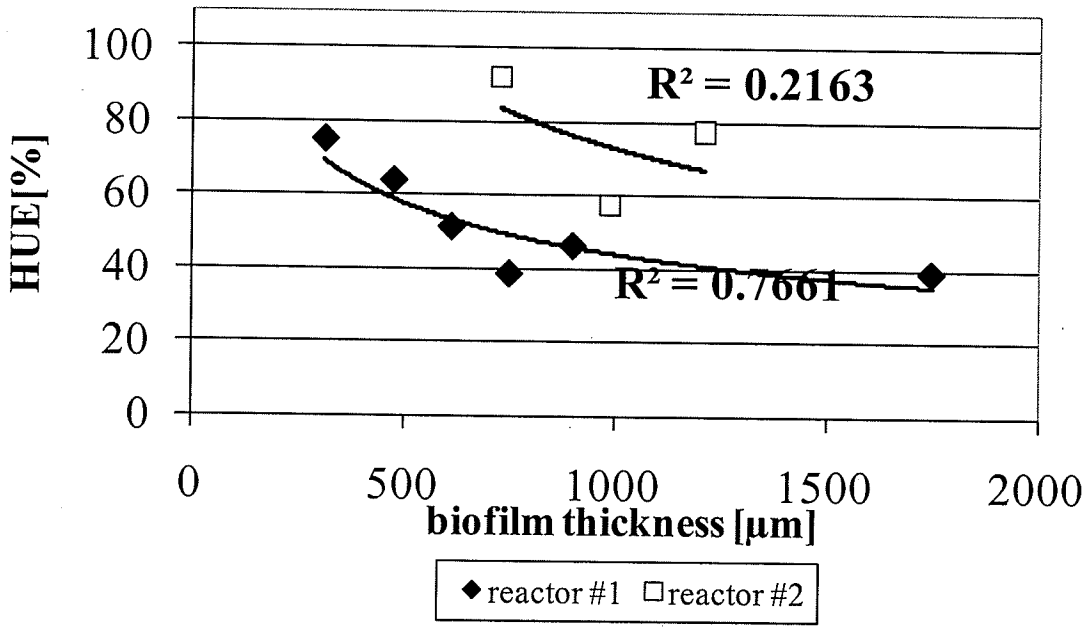


Figure 5.14 Power relationships between biofilm thickness and hydrogen utilization efficiency (HUE)

5.4 CONCLUSIONS

The study demonstrated that shear force can be used to effectively control the biofilm structure and therefore performance of MBfRs. Based on experimental data the following specific conclusions were formulated:

1. Higher shear force applied to a hydrogenotrophic denitrification MBfR improved denitrification rates by reducing biofilm thickness.

2. Intensive mixing decreased the biofilm thickness to ~ 800 µm. Additional nitrogen sparging facilitated further decrease of thickness to ~ 300 µm.

3. The highest average and maximum denitrification rates, equal to 0.93+/-0.14 g NO_3-N $m^{-2}d^{-1}$ and 1.20 g NO_3-N $m^{-2}d^{-1}$ respectively, were obtained at the highest applied shear force.

4. Higher nitrate removal was associated with lower EPS accumulation observed in thinner biofilms.

5. Lower carbohydrates to protein ratio (c/p) observed in denser biofilms corresponded to better removal efficiency.

6. Lower shearing stress resulted in solids accumulation at the biofilm surface.

Higher shearing stress limited this process, additionally causing shearing of the biofilm surfaces. However no significant sloughing of biomass was observed during steady state conditions.

7. During steady state operation, no significant change in total and soluble COD between the incoming wastewater and reactor effluent was observed.

CHAPTER 6: OPTIMIZING ULTRASOUND TREATMENT FOR IMPROVEMENT OF THE PERFORMANCE OF A MEMBRANE BIOFILM REACTOR FOR TERTIARY HYDROGEN- DRIVEN DENITRIFICATION OF MUNICIPAL WASTEWATER[5]

6.1 INTRODUCTION

As described in previous chapters, the applicability of the fiber – membrane biofilm reactor for tertiary wastewater treatment depends on stability of operation. Previous experiments showed that denitrification efficiency in MBfR can be strongly repressed by limitation in hydrogen (Celmer et al. 2006) or in nitrate diffusion in the thick biofilm (Beyenal and Lewandowski, 2000, Essila et al., 2000). This may lead to dual diffusive limitations, which was described by Terada et al. (2006) who observed the deterioration of denitrification efficiency as biofilm structure changed. One of the main concerns is thus excess biofilm development, which may lead to lower efficiency, biofilm sloughing and brings the risk of breakthrough of total and volatile solids as well as COD into the effluent (Lee and Rittmann, 2003). Controlling biofilm structure i.e. its thickness, density and composition is then a key factor which affects membrane biofilm reactors efficiency. Different methods were tested in order to verify its feasibility to control MBfR performance. Nutrient starvation conditions limit biofilm growth and maintain stable but fairly low removal rates (Celmer et al., 2006). Increasing mixing shear stress or sparging reactor contents with nitrogen gas allowed minimizing biofilm accumulation and led to

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Impact of ultrasound treatment on biofilm structure and performance of the membrane biofilm reactor for tertiary hydrogen- driven denitrification of wastewater
D. Celmer, J. Oleszkiewicz, N. Cicek

relatively good denitrification rates (Celmer et al., 2008). The issue of uneven exposure of biofilm to shear force while applying mixing and nitrogen sparging is the main disadvantage of this, otherwise very promising method. Usually outer fibers experience more shear force than the fibers inside the membrane bundle, which results in different biofilm morphology. Ultrasound treatment can be another option used for creating a shear force within the MBfR.

Ultrasound is able to deagglomerate bacteria clusters or inactivate bacteria through a number of physical, mechanical and chemical effects arising from acoustic cavitations. On collapse, cavitiation bubbles produce enough energy to mechanically weaken or disrupt bacteria via a number of processes such as shear forces induced by microstreaming within bacterial cells, resonance of bacterial cells or chemical attack due to the formation of radicals (Mason et al., 2003).

So far ultrasounds have been applied to membrane system as the treatment minimizing membrane fouling. The evaluated dosages varied depending on the ultrasound power, frequency and time of exposure. Wen et al. (2007) applied ultrasound for 2 min per 15 min (28 kHz, 300 W) which resulted in cleaning the membrane. Higher ultrasound frequency (70 - 500 kHz) required 2 hours of exposure to ultrasound to clean the membrane surface (Peterson and Pitt, 2000). Tests identified two main mechanisms which were responsible for membrane cleaning (i.e. removal of biofilm). The created shear effect resulted from collision of micro particles with the membrane surface and chemical reactions between the membrane and hydroxyl radicals produced during acoustic cavitations (Wen at al., 2007). The ultrasound was shown to be efficient in improving membrane permeability and mitigate membrane fouling (Chai et al., 1999,

Kobayashi and Hosaka, 2003, Bott and Tianqing, 2004). Ultrasonication is also known to increase the transport of substances across the biofilm that normally block or slow such movement. Peterson and Pitt (2000) observed and described with mathematical model that transport of antimicrobial substances within pores of the biofilm increases during ultrasound treatment with lower intensities and decreases for higher frequencies. One explanation for biofilm recalcitrance is the existence of extracellular polymeric substances (EPS) that establish a diffusion barrier or bind the substances before they can reach the bacterial cells (Huang et al., 1996). Several mechanisms have been hypothesized as the source of the bioacoustic effect for improved transport within biofilm (Qian et al., 1996). Foremost, ultrasounds are believed to enhance the transport of substances through the biofilm to the surface of bacterium or to break up the biofilm therefore exposing a larger number of the bacteria to environement (Qian et al., 1996). Another theory claims that ultrasounds improve the transport through the cell membrane. Other factors which could contribute to improved transport within the biofilm after sonication could be: increased microconvection from ultrasonic heating, ultrasonic vibrational interactions with bubbles (cavitation events), reduction of boundary layer thickness due to turbulence or microconvection or "oscillatory – enhanced dispersion" caused by oscillatory flow in channels (Carmen et al., 2004). Some experiments tend to discount the possible role of cavitation as micrographs of biofilm do not show many voids that could serve as nuclei for cavitation bubbles (Carmen et al., 2004) or did not show the change in structure of the biofilm or the spatial arrangement of the cells (Qian et al., 1996). Ultrasound is known to enhance the transport of small molecules across

polymer membranes and gels, and then, if similar process occurs in biofilms, increased transport might saturate available binding sites more rapidly (Carmen et al., 2004).

Thus ultrasound treatment could be effective in minimizing the biofilm thickness and controlling membrane biofilm reactor performance however optimizing the ultrasound dosage is crucial in order to prevent the undesired negative impact such as killing of bacteria or COD release.

The ultrasounds can also provide powerful killing effect (percent of kill bacteria). The tests showed that increasing the duration of exposure and intensity of ultrasounds in the low kilo- hertz range (20kHz and 40kHz) leads to the bacteria inactivation. Low intensity ultrasounds (higher frequencies) result in declumping, low kill rate and no significant decrease in bacterial cell numbers (Mason et al., 2003, Joyce et al., 2003). The low frequency treatment showed good penetration of the liquid (such as wastewater) by the ultrasound waves, which suggests its better applicability for large volume tanks (Mason et al., 2003).

The tests showed high resistance of the attached bacteria clusters to the ultrasound treatment suggesting that it could be a feasible source of shear force within MBfR. Oulahal et al. (2007) showed that even application of low frequency ultrasound (10s at 40 kHz) failed to remove all the biofilm and addition of EDTA and enzymes solutions was required to obtain 100 % biofilm removal. Peterson and Pitt (2000) found that ultrasound treatment was not significantly detrimental to biofilm viability which was attributed to protection barrier created from extracellular polymeric substances (EPS) matrix and resulted only in de-clumping effect. Application of lower frequencies ultrasound could be then useful tool for controlling biofilm thickness, improving mass transport conditions

with no significant negative impact on biofilm viability. Even though the attached bacterial clusters showed high resistance to ultrasounds (Oulahal et al., 2007; Peterson and Pitt, 2000) the negative impact of ultrasounds on bacteria viability may be an important disadvantage thus proper ultrasound dosage has to be determined in order to prevent inactivation of bacteria and consequent possible deterioration of removal efficiency.

It should be noted that application of ultrasounds can cause the release of organic matter into solution and thus lead to increase in the chemical oxygen demand (COD) of the treated stream. The release of the substances can be a result of rupture of the bacterial cells or the extraction of EPS. When EPS extraction was caused by ultrasound treatment, it has shown a relatively high yield of extraction of carbohydrates (7% of biomass weight), proteins (10% of biomass weight), humic substances (5% of biomass weight) and uronic acids (2.5% of biomass weight) from EPS matrix (Liu et al., 2002). On the other hand, with sonication, H_2O is known to decompose in collapsing cavitation bubbles to yield OH• radicals (Kotronarou et al., 1992, Lin et al., 1996, Wu et al., 1992). These radicals diffuse into the bulk liquid and increase the radical concentration in the solution thus enhancing the decomposition rate of organic matter (James et al., 1995).

Properly selecting the ultrasound intensity and working time could be an effective way of controlling the biofilm thickness, structure and the MBfR performance.

6.1.1 Objectives

This study aimed to investigate the application of ultrasound treatment to autotrophic denitrification of low organic carbon content wastewater within a biofilm growing on a

hydrogen diffusing membrane. The objective of the experiment was to evaluate impact of different dosages of the ultrasound expressed by different time of the exposure, on the process rates, as well as biofilm parameters by measuring the impact of ultrasound on the biofilm structure (i.e. biofilm thickness, density), biofilm viability, denitrification rates and effluent quality (total and volatile solids concentration, chemical oxygen demand).

6.2 MATERIALS AND METHODS

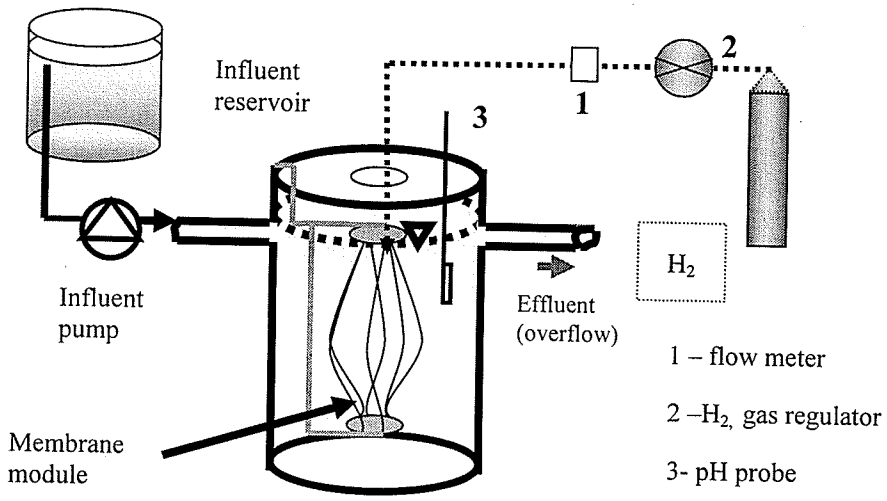
6.2.1. Reactor Operation

The experimental set-up involved two laboratory-scale biofilm reactors with volume of 3 L. The reactors were operated in continuous flow mode with hydraulic retention time of (HRT) 4 hours. This low operational HRT was chosen in order to evaluate the system under high loading (i.e. minimized tank volume). The bioreactors were seeded with a population of autotrophic denitrifiers at the first day of the operation. Hydrogen necessary for the process was delivered through the submerged fibre membrane module (GE Water & Process Technologies - ZENON Membrane Solutions). The detailed description of the membrane can be found in Table 5.1. Constant hydrogen supply at the pressure of ~2.5- 4 psi (1 psi= ~ 10 kPa) was maintained throughout the experiment which assured that hydrogen was not a limiting component.

One of the reactors was placed in the ultrasound bath (FS220 Ultrasound Cleaner, power 250W and frequency 44KHz (+/-6%) (Figure 6.1(b)) and exposed to the ultrasound treatment. Three different dosages of the ultrasounds expressed by the different times of exposure were tested. The regime of ultrasound treatment is presented in Table 6.1. The

ultrasound dosage was chosen basing on the literature review. No external shear force was applied to the second system (control conditions)(Figure 6.1.(a)).

(a) control reactor



(b) testing reactor

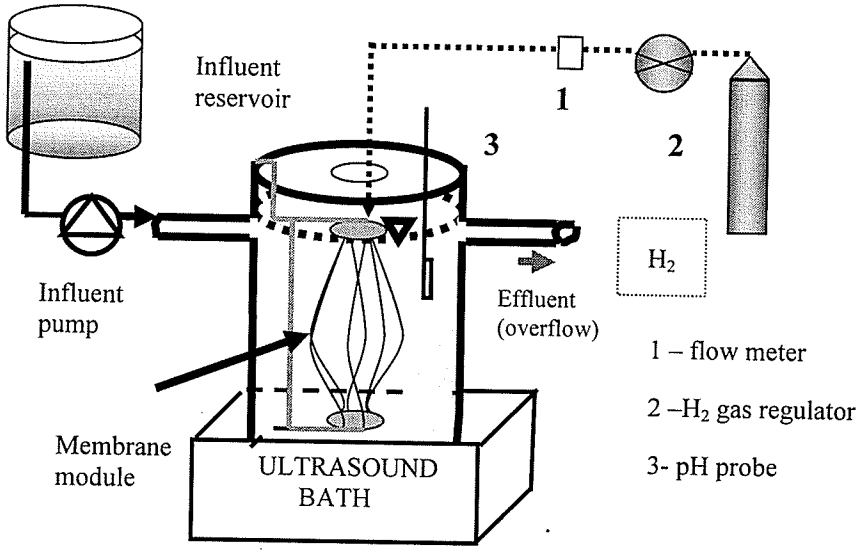


Figure 6.1 Membrane biofilm reactor set – up

The reactors were fed with un-disinfected final effluent collected from the City of Winnipeg-North End secondary wastewater treatment plant. Nitrates were added to the feed in the form of $NaNO_3$. The main influent wastewater parameters are presented in Table 6.2. No pH control was implemented.

Table 6.1 Ultrasound regime

	operating conditions
phase 1	no shear force
phase 2	ultrasound treatment - 15 sec twice a day
phase 3	ultrasound treatment - 60 sec twice a day
phase 4	ultrasound treatment - 120 sec twice a day

Table 6.2 Feed wastewater characteristics

(a) control reactor

Parameter	Units	phase 1	phase 2	phase 3	phase 4
Influent NO_3-N	mg l^{-1}	41.3+/-7.9	34.86+/-4.7	34.1+/-6.2	31.8+/-1.5
SCOD	mg l^{-1}	42+/-4	60+/-1	46+/-6	41+/-6
alkalinity	mg $CaCO_3$ l^{-1}	222+/-22	255+/-22	253+/-47	233+/-47
temeprature	°C	17.5+/-1.2	19.2+/-0.8	20.5+/-0.6	21.6+/-1.9
DO	mg l^{-1}	1.4+/-0.9	0.3+/-0.4	0+/-0.1	2.3+/-2.5
pH	-	7.11+/-0.13	7.23+/-0.18	7.37+/-0.26	7.17+/-0.66

(b) testing reactor

Parameter	Units	phase 1	phase 2	phase 3	phase 4
Influent NO_3-N	mg l^{-1}	34.8+/-4.4	32.6+/-4	33.8+/-6	31.8+/-1.5
SCOD	mg l^{-1}	39+/-7	66+/-8	52+/-12	53+/-11
alkalinity	mg $CaCO_3$ l^{-1}	219+/-30	245+/-36	250+/-51	236+/-48
temeprature	°C	17.6+/-1.3	19.2+/-0.5	20.6+/-0.8	21.0+/-0.6
DO	mg l^{-1}	2.12+/-1.4	0.40+/-0.8	0.0+/-0.1	2.0+/-1.1
pH	-	7.09+/-0.07	7.18+/-0.06	7.30+/-0.3	7.20+/-0.30

Note 1: changes in the DO concentration where related to the changes in quality of incoming wastewater (seasonal changes)

Note 2: NO3-N concentrations in influent in phases 1, 2, 3, 4 are: 41.3+/- 12.8, 34.8+/- 4.7, 34.1+/-8.1, 33.9+/- 3.6 in control reactor and 34.8+/- 4.4, 32.6+/- 4.2, 33.8+/- 6.0, 33.9 +/- 3.8 in testing reactor.

6.2.2. Analytical Methods

Influent and effluent samples were collected daily for NO_3, NO_2, TSS and VSS analysis. Samples of influent and effluent for NO_3-N, NO_2-N and COD analysis were taken each day of the reactor operation and stored at ~ 4°C. NO_3 and NO_2 concentrations, COD concentrations as well as DO and pH, TSS and VSS values in the reactor were measured according to procedures presented in Chapter 2, points 2.3.1 and 2.3.2. The measurements were taken in room temperature and all presented denitrification rates were calculated for 20°C.

Biofilm samples for thickness and density were collected from the membrane surface once per week after application of ultrasound treatment. The module with biofilm was removed from the reactor for 10 min and placed in vertical position to allow excess water to drain. The samples of known surface area were removed from module with a wooden spatula and put into a 5ml plastic syringe which was partially filled with de-ionized water and sealed. The biofilm thickness and density was determined according to procedure described in details in Chapter 2, point 2.3.3.

Carbohydrates and proteins content within the biofilm were determined using the Anthrone (Viles and Silverman, 1949) and modified Bradford method with glucose and BSA standards, respectively.

The characterization of the extracellular polymeric substances (EPS) bound within the biofilm were carried out by measuring the dry weight content (at 105 °C) of extracted EPS. The EPS were extracted in three steps: (1) addition of DOWEX MARATHON C cation exchange resin and extraction (2 h at 20°C), (2) centrifugation (10000 rpm, 10 min) and (3) acetone and ethanol precipitation (24 h at 4°C) (Comte et al., 2004). The detailed description of the EPS content determination is presented in Chapter 2, point 2.3.2.

The viability of cells was determined with LIVE/DEAD BacLight Bacterial Viability Kit (L7012) through quantitative assays with RF-1501 SHIMADZU Spectorofluorophotomer (P/N 206-62901) with PC-1501 Personal Fluorescence Software. The tests were carried out according to procedure suggested by kit provider (Molecular Probes Invitrogen detection technologies) which is presented in detail in Chapter 2, Point 2.3.3. The structure of the membrane fibers were analyzed with Cambridge Stereoscan 120 Scanning Electron Microscope with black scattered electron detector, energy dispersive X-ray detector and digital image store facility.

6.3. RESULTS AND DISCUSSION

6.3.1. Impact of different ultrasound dosages on biofilm thickness and density

The biofilm structure i.e. its thickness and density was a function of levels of applied ultrasound dosage to the biofilm. Fluctuations in biofilm structure (i.e. its thickness and

density) during the testing periods are presented in Figure 6.2 and Figure 6.3. Different operating shearing stress regimes resulted in different thickness of biofilm covering the membrane. Lack of any shear force (control conditions) resulted in increase of biofilm thickness in the reactor over time. The biofilm thickness in control reactor increased continuously due to biofilm development (bacteria growth and particles attachment) and measured thicknesses were equal to 410+/-151μm (95% CI 303 to 513 μm), 597+/-114μm (95% CI 506 to 689 μm), 622+/-254μm (95% CI 443 to 800 μm), and 813 +/-255 μm (95% CI 408 to 1216 μm) in following phases.

Application of ultrasound allowed the reduction of biofilm accumulation; no increase in biofilm thickness was observed. The lowest tested dosage of ultrasound (15 sec twice a day in phase 2) allowed to slightly reduce the average biofilm thickness from 685 +/- 406 μm (95% CI 399 to 970 μm) to 500+/-155 μm (95% CI 423 to 572 μm), however no significant difference in thickness was observed. Further increase in applied ultrasound dosage (up to 60 sec twice a day) did not result in additional decrease in biofilm thickness. Exposing biofilm to ultrasound for 1 minute twice a day allowed to obtain biofilm with the average thickness or 540+/-43 μm (95% CI 336 to 714 μm). Finally the highest tested dosage (2 minutes, twice a day) resulted in reduction of biofilm thickness to 372+/-45 μm (95% CI 324 to 418 μm). In spite the fact of observed decreasing trend in average biofilm thickness the statistical comparison of phases with T test did not show significant difference due to large standard deviation in obtained biofilm thicknesses in following phases (Figure 6.2). This large standard deviation was attributed to fluctuations in biofilm morphology along the membrane fibers. It also indicates the application of the ultrasound does not provide for a very even impact of shear force on all the fibers within

a membrane. However comparison of biofilm thickness in phases with no shear force and with highest ultrasound dosage (120 sec twice a day) showed significant difference. When no mixing or ultrasound treatment was applied to the system biofilm thickness averaged 813+/-255 μm due to accumulation of solids on the biofilm surface. Ultrasound treatment (the highest dosage) resulted in reduction of biofilm thickness to 372+/-45 μm. The T test comparing those two phases confirm significant change with p value equal to 0.0407 suggesting that ultrasound treatment can be a viable method of minimizing biofilm accumulation. The detailed results of statistical analysis of thickness in following phases are presented on the Figure 6.2.

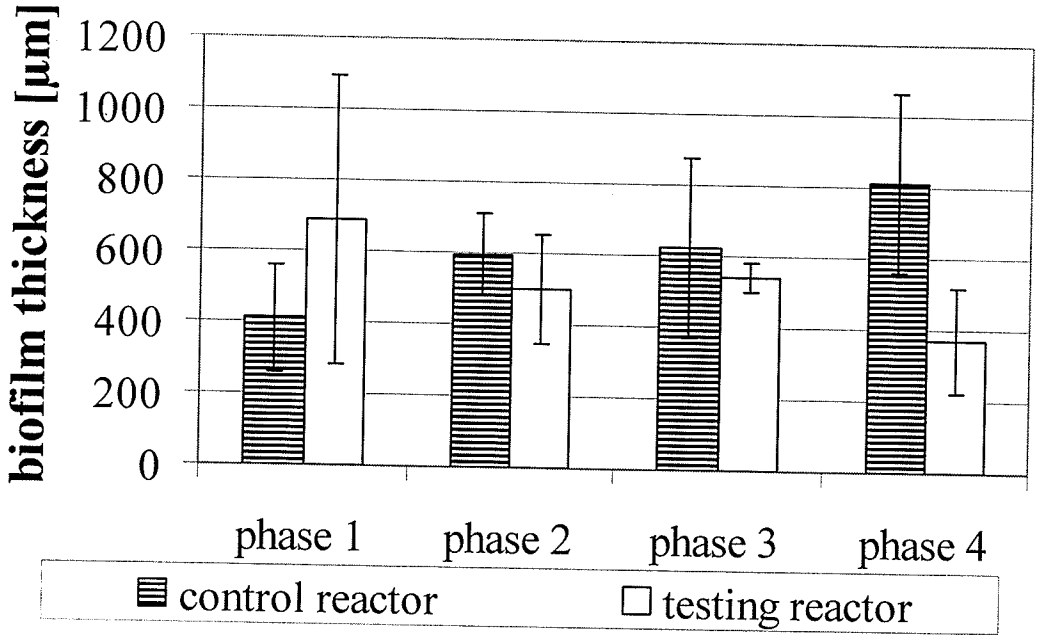


Figure 6.2 Fluctuations in biofilm thickness in control reactor and reactor exposed to ultrasound treatment (10 duplicates per phase). *Phase 1- no shear; Phase 2 – ultrasound treatment – 15 sec a day; Phase 3 – ultrasound treatment – 60 sec a day; Phase 4 – ultrasound treatment – 120 sec a day*

p values for comparison of control and testing reactor

phase 1v1	*phase 2v2*	*phase 3vs3*	*phase 4vs4*
0.13277	*0.38683*	*0.46111*	*0.04907*

p values for testing reactor

phase 1vs2	*phase 1vs3*	*phase 1vs4*
0.22043	*0.33606*	*0.18421*

p values for control reactor

phase 1vs2	*phase 1vs3*	*phase 1vs4*
0.05549	*0.11472*	*0.05533*

The results of simultaneous measurements of biofilm density are shown on Figure 6.3. Comparison between the control and testing reactors did not show significant changes suggesting that gradual exposing to ultrasound biofilm with relatively high TS content does not affect biofilm density. Also, no significant changes in total and volatile solids

content within biofilms exposed to increasing ultrasound dosages were observed. The initial total and volatile solids concentrations in testing reactor were equal to 97+/-3 g TS l^{-1} (95% CI 90 to 101 g TS l^{-1}) and 58 +/-9 g VS l^{-1} (95% CI 50 to 68 g VS l^{-1}) Exposure to the lowest dosage of ultrasound treatment did not cause significant changes in biofilm density and measured total and volatile solids content was equal to 99+/-40 g TS l^{-1} (95% CI 71 to 127 g TS l^{-1}) and 61+/- 23 g VS l^{-1} (95% CI 45 to 77 g VS l^{-1}) respectively. Medium dosage resulted in creation of the biofilm with similar density of 79+/-11 g TS l^{-1} (95% CI 72 to 87 g TS l^{-1}) and 52+/-10 g VS l^{-1} (95% CI 51 to 52 g VS l^{-1}) Also the highest applied dosage (2 minutes, twice a day) did not cause any significant changes in biofilm density. The detected total and volatile solids content was 90+/- 13 g TS l^{-1} (95% CI 77 to 104 g TS l^{-1}) and 52+/- 8 g VS l^{-1} (95% CI 44 to 61 g TS l^{-1}) respectively. The previous studies involving increased levels of shear stress caused by mixing, gas sparging demonstrated that the higher the shear forces the thinner and denser biofilm (Liu and Tay, 2002; Ohashi and Harada, 1994; Kwok et al., 1998). Also other researchers observed that biofilms created in high shear stress conditions are more compact (less porous) than those created under lower shear conditions (Livingston and Santos, 1995; Viera M.J., 1993). This further leads to drop of effective diffusivity within biofilm and decrease in system's efficiency (Viera M.J., 1993). Application of ultrasound allowed for some reduction of biofilm thickness without the simultaneous increase in biofilm density.

The observed VS/TS ratio remained unchanged regardless the changes in the applied dosage of ultrasound and levelled at the value of 0.60+/-0.02. Previously obtained results presented in Chapter 4, Point 4.3.3 indicate that biofilms carrying out hydrogenotrophic denitrification can contain high content of inert solids and that a VS/TS ratio higher than

0.25 needs to be maintained to assure stable biofilm operation and prevent biofilm sloughing.

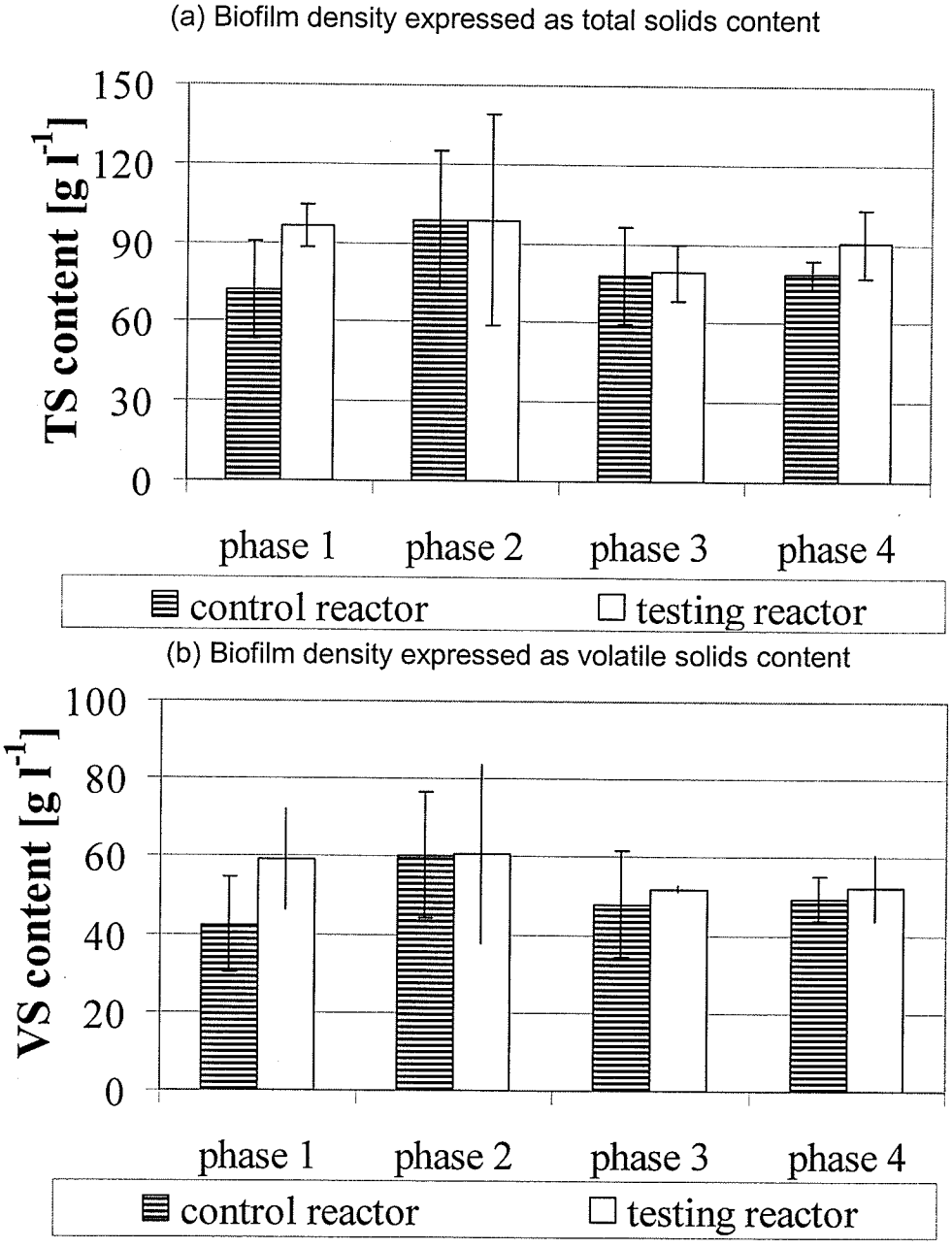


Figure 6.3 Fluctuations in biofilm density in control reactor and reactor exposed to ultrasound treatment (10 duplicates per phase) *Phase 1- no shear; Phase 2 – ultrasound treatment – 15 sec a day; Phase 3 – ultrasound treatment – 60 sec a day; Phase 4 – ultrasound treatment – 120 sec a day*

6.3.2. Impact of different ultrasound dosages on bacteria viability

Data presented on the Figure 6.4 show changes in bacteria viability within the biofilm for different operating conditions. The determined viability of bacteria in MBfR varied from 10 % to 53 % of all bacterial cells depending on the location within a membrane bundle and applied dosage of the ultrasound. The initial measurements show fairly low bacteria viability on the average equal to 23+/- 12 % (95% CI 4 to 42%). Viability within a biofilm increased to 35+/-2 % (95% CI 32 to 38%) after the second phase of testing period, when biofilm was exposed to ultrasound for only 15 seconds, twice a day. However comparison of the results showed no significant difference due to the large fluctuation in viability measured within a biofilm before introduction of ultrasound treatment. Further increase in ultrasound dosage resulted in subsequent increase in biofilm viability. The viability within a biofilm after 3rd phase was equal to 46+/-8% (95% CI 33 to 59%). It has been speculated that shear force resulting from the ultrasound treatment allowed removing the dead cells and thus led to observed increase in average viability of the biofilm. Overall no negative impact of the tested dosages (15 sec and 60 sec twice a day) on viability was observed.

However, the results obtained in the fourth phase showed reduction of bacteria viability to 15 +/- 1% (95% CI 13 to 17%) suggesting that biofilm population is susceptible to this ultrasound dosage (2 minutes, twice a day). Careful choice of proper dosage has to be done in order to prevent killing of bacteria.

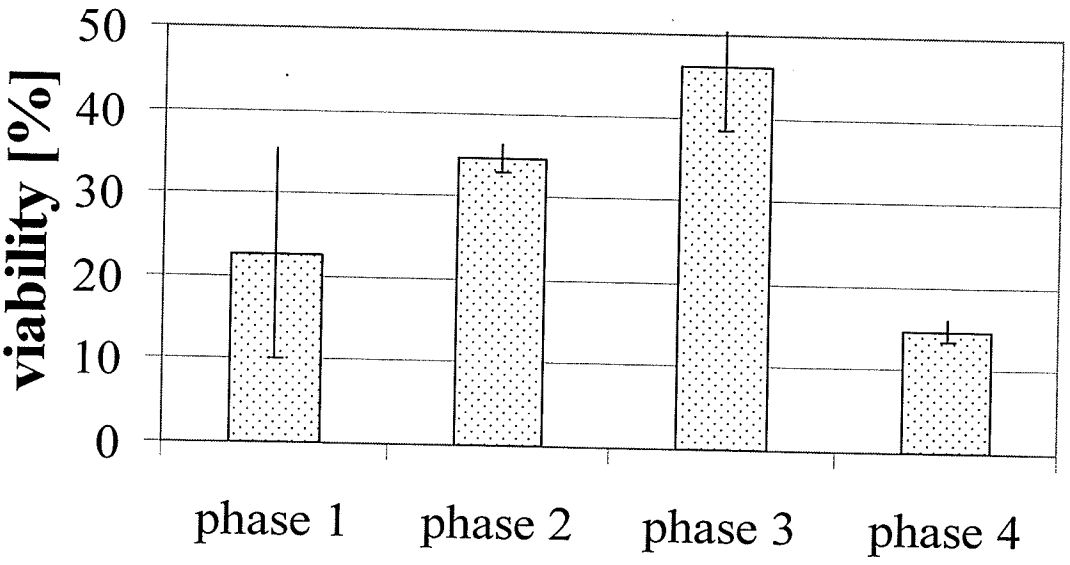


Figure 6.4 Impact of ultrasound on bacteria viability (4 duplicates per phase)

6.3.3. Impact of ultrasound on EPS accumulation and biofilm composition

The obtained results suggest that application of ultrasound allows changing the biofilm thickness. Data presented in Figure 6.5 show the changes in EPS, protein and carbohydrates content within the biofilm for different operating conditions. The measurements showed that EPS content remained similar in reactors with no shear force (63+/-5 mg $EPSgVS^{-1}$; 95% CI 60 to 67 mg $EPSgVS^{-1}$) and with ultrasound treatment (100+/-102 mg $EPSgVS^{-1}$; 95% CI 28 to 171 mg $EPSgVS^{-1}$). These results suggest that while hydrodynamic shear force is known to stimulate EPS production (Ohashi and Harada, 1994; Pratt et al, 1999, Trinet et al, 1991), ultrasound treatment does not affect EPS accumulation within this biofilm.

The main components of the EPS are carbohydrates, proteins as well as nucleic acids and lipids (fatty acids, glycerol, and phosphate) (Moran and Ljungh, 2003). Although the carbohydrates have often been regarded as the most important extracellular components (Christensen, 1989), proteins were found at relatively higher levels than carbohydrates in

this study. Protein concentrations varied from 51+/- 26 mg proteins (g VS)$^{-1}$ to 84+/-6 mg proteins (g VS)$^{-1}$, while concentrations of carbohydrates varied from 25+/-9 mg carbohydrates (g VS)$^{-1}$ to 31+/-11 mg carbohydrates (g VS)$^{-1}$. This observation is consistent with work by Jahn and Nielsen (1998) who also observed that proteins and humic substances were the main components of biofilms. The calculated carbohydrates to proteins ratio (c/p ratio) varied from 0.2 to 0.6, which is also comparable to the results obtained by Jahn and Nielsen who analyzed sewer biofilms and observed c/p between 0.25-0.6.

However contrary to previous research, where higher shear force led to overproduction of carbohydrates (Ohashi and Harada, 1994; Pratt et al, 1999; Trinet et al, 1991), the results of this study did not show any significant correlation between carbohydrates content (c) and shear force caused by ultrasound treatment. The results presented on Figure 6.5 show that carbohydrates content remained unchanged regardless of changes in applied shear stress. It was equal to 25+/-10 mg g VS^{-1} (95% CI 20 to 39 mg g VS^{-1}) and 31+/- 11 mg g VS^{-1} (95% CI 26 to 37 mg g VS^{-1}) in reactor operated without any shear force and reactor exposed to ultrasound treatment respectively.

The fraction of proteins was however affected by ultrasound treatment. The protein content decreased from 84+/-6 mg g VS^{-1} (95% CI 81 to 87 mg g VS^{-1}) when no shear force was applied to 51+/- 25 mg g VS^{-1} (95% CI 40 to 64 mg g VS^{-1}) in the reactor exposed to ultrasound treatment. The change was attributed to fragmentation of protein by hydroxyl radicals created during ultrasound treatment and possible glycolytation i.e. binding of sugar molecule to a protein to produce glycoproteins (1986; Hunt et al., 1988). The proteins can be also substituted with fatty acids to yield lipoproteins (Horan and

Eccles, 1986). This resulted in a change in calculated carbohydrates to protein ratio (c/p). Figure 6.6 represents the changes in c/p ratio for different operating regimes. The results suggest that ultrasound treatment may lead to increase in c/p ratio. It increased from 0.30+/-0.09 when no shear stress was applied to 0.75+/-0.42 in reactor exposed to ultrasound treatment. It is believed that proteins provide most of the binding sites within a biofilm (Higgins and Novak, 1997; Houghton and Quambry, 1999). Thus increased c/p ratio caused by ultrasound might lead to risk of biomass sloughing, VSS and COD breakthrough in the effluent.

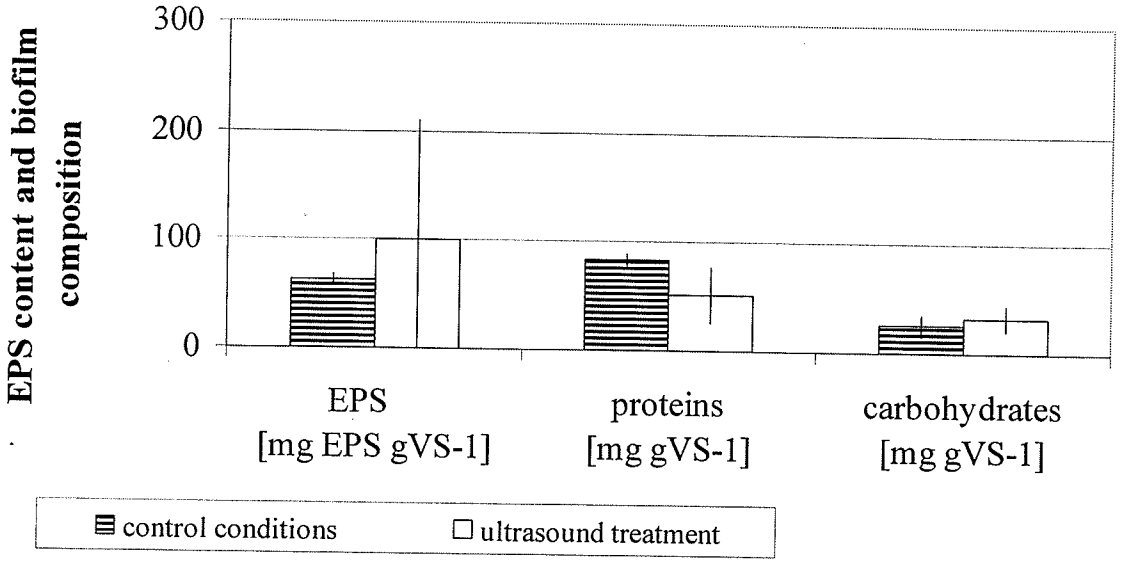


Figure 6.5 Fluctuations in EPS, proteins and carbohydrates content for different shearing stress regimes (the vertical line indicates the standard deviation) (10 replicates per each phase)

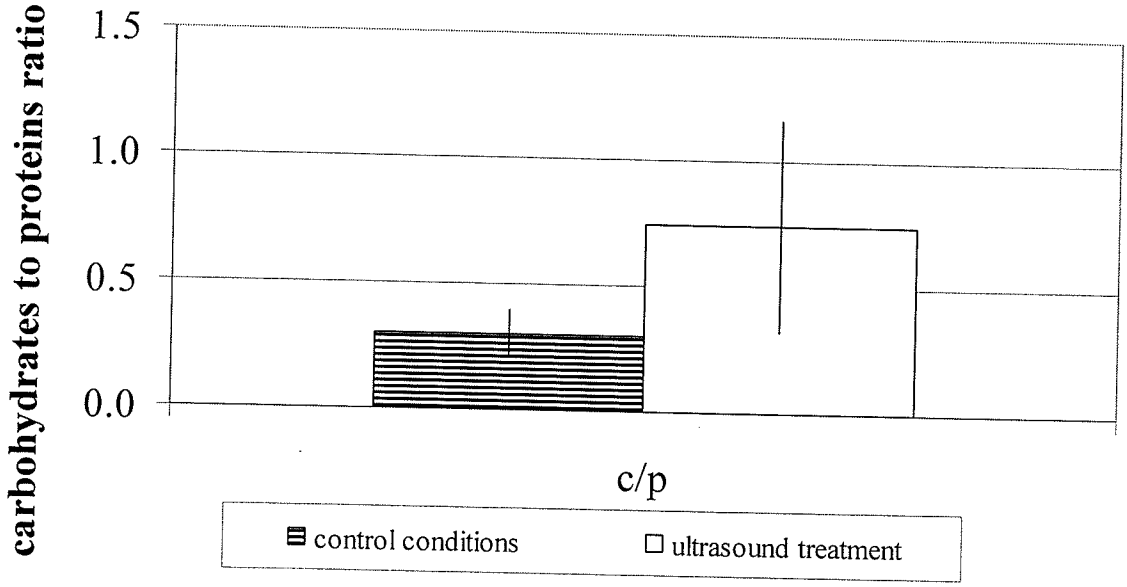


Figure 6.6 Fluctuations in c/p ratio for different shearing stress regimes (the vertical line indicates the standard deviation)

6.3.4. Impact of different ultrasound dosages on denitrification rates

The ultrasound treatment affected the denitrification rates by altering the biofilm thickness, structure and bacteria viability (the significant difference only between phase 1 and 4). Denitrification rates obtained for different shearing stress regimes are presented in Figure 6.7. The initial denitrification rate was low and equal to only 0.58+/- 0.23 gNO_3-N $m^{-2}d^{-1}$ (95% CI 0.49 to 0.67 gNO_3-N $m^{-2}d^{-1}$) indicating the importance of limitation in diffusion caused by increased biofilm thickness (685+/-406 μm) and laminar flow conditions. Application of lowest ultrasound dosage allowed for a slight decrease of the biofilm thickness (500+/-155 μm). The detected removal was in range on 0.68+/-0.11 gNO_3-N $m^{-2}d^{-1}$(95% CI 0.64 to 0.72 gNO_3-N $m^{-2}d^{-1}$). However, as for biofilm thickness measurements, no statistical difference in obtained denitrification rate for this dosage was

determined. Further increase in ultrasound dosage did not result in decrease in the biofilm thickness either (540 +/-43 μm) however some increase in average removal rate was observed as the rate obtained in third phase was equal to 0.80+/-0.10 gNO_3-N $m^{-2}d^{-1}$ (95% CI 0.77 to 0.83 gNO_3-N $m^{-2}d^{-1}$).

Introduction of the highest ultrasound dosage allowed for minimizing biofilm thickness (372+/-45 μm) and further improvement in denitrification rates. Application of ultrasound for 2 minutes twice a day resulted in the highest denitrification rate equal to 1.12+/- 0.20 gNO_3-N $m^{-2}d^{-1}$ (95% CI 1.07 to 1.17 gNO_3-N $m^{-2}d^{-1}$).

The comparison of the denitrification rate obtained without any shear force (0.58+/- 0.23 gNO_3-N $m^{-2}d^{-1}$) with the rate observed for the highest ultrasound dosage (1.12+/- 0.20 gNO_3-N $m^{-2}d^{-1}$) showed the significantly beneficial impact of the ultrasound treatment. A t-test conducted on the data comparing these two phases show significant differences in denitrification rates obtained in control and testing reactor ($p = 0.031$, $p= 1.17* 10^{-16}$ and $p =1.68*10^{-10}$ for three different ultrasound dosages), indicating that ultrasound can be used to control removal rates.

The detailed comparison of the rates obtained in the reactor exposed to ultrasound and control reactor show the beneficial impact of ultrasound treatment and the impact of the biofilm thickness on removal rates. The increase in biofilm thickness observed in control reactor (Figure 6.2) resulted in continuous decrease on denitrification efficiency (Figure 6.7). Removal of parts of biofilm due to ultrasound treatment and minimizing the biofilm thickness (especially in phase 4; Figure 6.2) allowed for increasing trend in obtained denitrification rates (Figure 6.7).

However ultrasound treatment seemed to improve the denitrifying bacteria efficiency not only due to minimizing the biofilm thickness. Figure 6.8 shows the correlation between biofilm thickness and denitrification rate for the control reactor and system exposed to ultrasound (testing reactor). The data obtained during phases including mixing and nitrogen sparging was also plotted on Figure 6.8. All sets of data show the inverse relationship between biofilm thickness and denitrification rate. Nevertheless, the increase of biofilm efficiency is much faster in the reactor exposed to ultrasound (Figure 6.8 shows the slope values for both of the system). These results seem to confirm previous observations that ultrasound improves diffusion of substrate within a biofilm due to possible improved transport through the EPS, increased microconvection from ultrasonic heating, ultrasonic vibrational interactions with bubbles (cavitation events), reduction of boundary layer thickness due to turbulence or microconvection or saturate available binding sites more rapidly (Carmen et al., 2004; Qian et al., 1996).

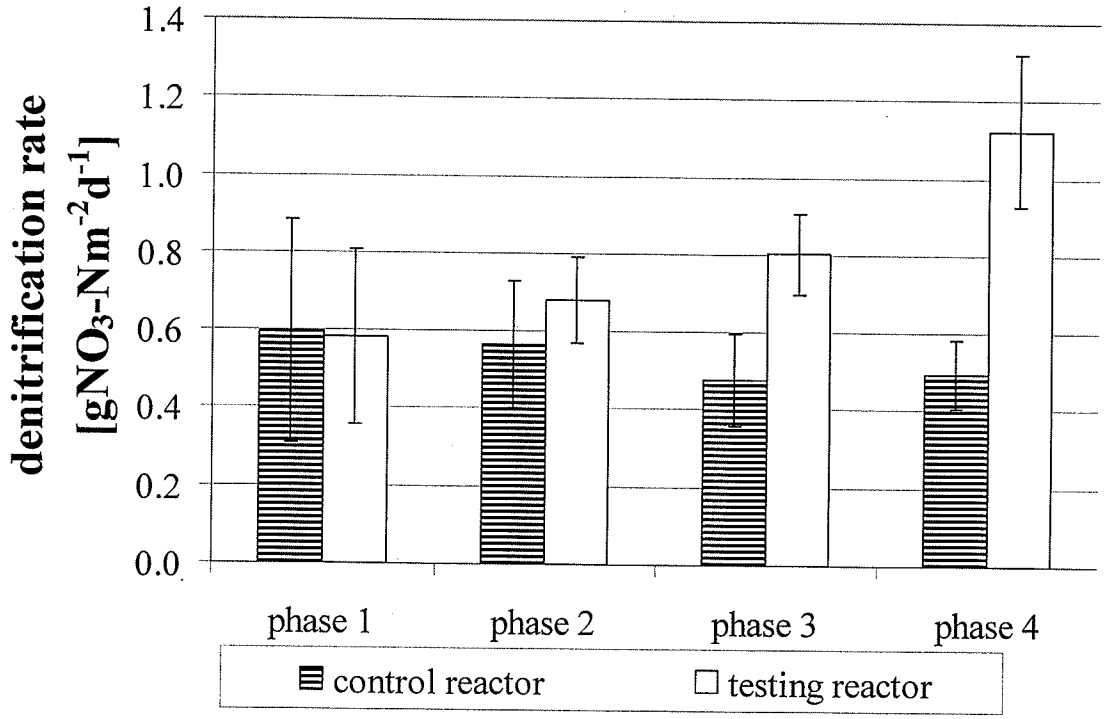


Figure 6.7 Denitrification rates obtained in control reactor and reactor exposed to ultrasound treatment (from 30 – 37 duplicated per phase) *Phase 1- no shear; Phase 2 – ultrasound treatment – 15 sec a day; Phase 3 – ultrasound treatment – 60 sec a day; Phase 4 – ultrasound treatment – 120 sec a day*

p values for comparison of control and testing reactor

phase 1v1	*phase 2v2*	*phase 3vs3*	*phase 4vs4*
0.85434	*0.03123*	$1.71 * 10^{-16}$	$1.68 * 10^{-10}$

p values for testing reactor

phase 1vs2	*phase 1vs3*	*phase 1vs4*
0.18946	*0.00012*	$4.65 * 10^{-19}$

p values for control reactor

phase 1vs2	*phase 1vs3*	*phase 1vs4*
0.57220	$4.9 * 10^{-4}$	*0.44254*

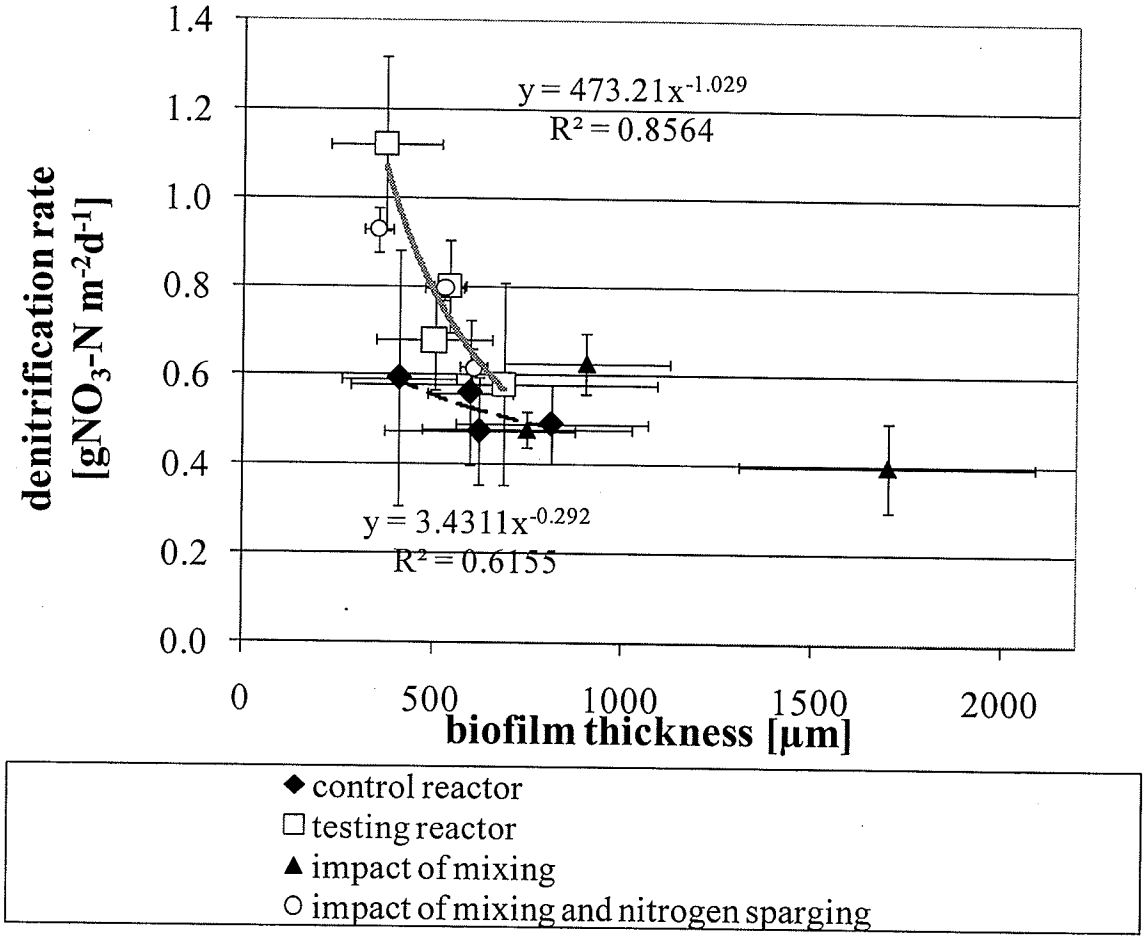


Figure 6.8 Correlation between the denitrification rate and biofilm thickness in control reactor and reactor exposed to ultrasound treatment

6.3.5 Impact of biofilm structure and composition on denitrification rate

Summary of the basic parameters of the biofilm is presented in Table 6.3. The results suggest that application of ultrasounfd allows changing the biofilm structure and thus affect the denitrification rates. The inversely proportional correlation between biofilm thickness and denitrification rates is presented in Table 6.3. This relationship was also observed in specific denitrification rates (SDR) calculated for phase 1,2, 3 and 4 which were equal to 0.18, 0.40, 0.49 and 1.63 mg NO_3-N *(h*g VS)$^{-1}$ respectively. These rates

were calculated basing on the known removal rates, membrane surface area and biofilm thickness and density. As such they are only approximation yet they suggest that activity of biomass increases which leads to higher observed denitrification rates. This increase was attributed to decrease in biofilm thickness, possible enhanced diffusion of substrate within a biofilm and improved transport through the cell membrane (Petterson and Pitt, 2000).

Table 6.3 Summary of biofilm parameters and obtained denitrification rates in reactor exposed to ultrasound

Parameter	Unit	No shear force	Ultrasound treatment [15 sec]	Ultrasound treatment [60 sec]	Ultrasound treatment [120 sec]
Thickness	μm	685+/- 406	500+/-155	540+/-43	372+/-45
Denisty based on TS	$g\ l^{-1}$	96+/-8	99+/-40	79+/-11	90+/-13
Density based on VS	$g\ l^{-1}$	59+/-13	61+/-23	52+/-1	52+/-8
Viability	%	23+/-13	35+/-2	46+/-8	15+/-1
Denitrification rate	$g\ NO_3N\text{-}N\ m^{-2}\ d^{-1}$	0.58+/-0.23	0.68+/-0.11	0.80+/-0.10	1.12.+/-0.20
Specific	$mg\ NO_3\text{-}N$	0.18	0.40	0.49	1.63
Hydrogen utilization efficiency	%	22+/-6	23+/-7	14+/-1	46+/-45

6.3.6. Solids and COD in influent

Successful application of the tested membrane biofilm reactor for polishing final effluent depends also on the obtained COD, TSS and VSS concentrations in the effluent, particularly if this is the last treatment step and there is no post-filtration.

After initial detachment of biomass due to the sudden change of hydrodynamic conditions (between testing phases) effluent solids stabilized at levels consistently below 20 mg l^{-1}, which is lower than presently adopted in Winnipeg discharge limit of 30 mg TSS l^{-1} from wastewater treatment plants. The results presented in the Table 6.4 (a) show that effluent obtained from the system operated without any shear force and thick biofilm

(685+/- 406 μm) is characterized by large fluctuations. Additionally, sloughing of biomass was observed which contributed to average effluent concentrations of total solid (16+/-10 mg l^{-1}) and volatile solids (13+/-8 mg l^{-1}) higher than values measured in the influent (7+/-2 and 5+/-2 mg l^{-1} of TSS and VSS). The VS/TS ratio in the effluent from reactor operated without any shear force was 0.8 suggesting that significant part of detached biofilm is organic matter sloughed probably due to limitation in diffusion in thick biofilm (685+/-406 μm). VS/TS ratio in effluent from reactor exposed to ultrasound was lower (0.6) suggesting that continuous shearing removes mostly inorganic biofilm content.

The results obtained for control reactor operated without any shear force but with low biofilm thickness (ca. 400- 500 μm) suggest continous attachment of solids which explains gradual increase in biofilm thickness (Figure 6.2). The concentrations of solids in effluent from this system were lower then those in the effluent and varied between 5-8 mg TSS l^{-1} and 3-4 mg VSS l^{-1} in four phases of the experiment (Table 6.4 (b)).

Ultrasound treatment allowed to maintain the effluent solids at the stable level similar to concentration measured in the influent. This further allows to minimize accumulation of solids within a biofilm. Results suggest that for treatment of wastewater with low solids concentration (~ 5 mg l^{-1}) lower dosages of ultrasound allow for sufficient removal of particles. The smallest dosage of ultrasound (15 sec twice per day) allowed to remove all the incoming solids (4+/- 3 mg TSS l^{-1} and 3+/-2 mg VSS l^{-1}). Higher incoming concentrations of solids require increased dosage of shear force (i.e. ultrasound exposure). Exposing biofilm to ultrasound for 2 minutes twice a day allowed to remove all the incoming solids in concentrations of 13+/-13 mg TSS l^{-1} and 7+/-2 mg VSS l^{-1}.

Table 6.4 Influent and effluent total and volatile solids and COD concentrations

(a) testing reactor

		Unit	TSS	VSS	TCOD	SCOD
No shear force	Influent	mg l^{-1}	7+/-2	5+/-2	62+/-0.5	51+/3
	Effluent	mg l^{-1}	16+/-10	13+/-8	60+/-19	54+/-3
Ultrasound treatment [0.25 min]	Influent	mg l^{-1}	4+/-3	3+/-2	73+/-15	66+/-8
	Effluent	mg l^{-1}	6+/-2	4+/-2	75+/-16	69+/-9
Ultrasound treatment [1 min]	Influent	mg l^{-1}	7+/-4	4+/-2	55+/-16	52+/-12
	Effluent	mg l^{-1}	10+/-2	7+/-1	58+/-16	55+/-10
Ultrasound treatment [2 min]	Influent	mg l^{-1}	13+/-13	7+/-2	58+/-10	53+/-10
	Effluent	mg l^{-1}	12+/0.3	7+/-2	83+/-20	60+/-17

(b) control reactor

		Unit	TSS	VSS	TCOD	SCOD
No shear force	Influent	mg l^{-1}	9+/-3	6+/-2	43+/-5	41+/- 4
	Effluent	mg l^{-1}	8+/5	5+/-4	53+/- 4	50+/- 2
Phase 2 [0.25 min ultrasound treatment in testing reactor]	Influent	mg l^{-1}	6+/-3	4+/3	50+/-13	46+/-9
	Effluent	mg l^{-1}	5+/-6	3+/-7	57+/- 10	52+/-5
Phase 3 [1 min ultrasound treatment in testing reactor]	Influent	mg l^{-1}	8+/- 3	5+/-3	40+/-5	45+/- 6
	Effluent	mg l^{-1}	6+/-6	4+/-5	55+/- 18	52+/- 6
Phase 4 [2 min ultrasound treatment in testing reactor]	Influent	mg l^{-1}	15+/-13	7+/-1	54+/-9	45+/-5
	Effluent	mg l^{-1}	7+/-2	4+/-1	53+/-7	48+/- 3

Total and soluble COD can be affected by VSS concentration and the excreted soluble EPS thus COD breakthrough is one of the main concerns for membrane biofilm reactors. Ultrasound treatment allowed to minimize the biofilm thickness due to declumping of biofilm and thus resulted in some increased total COD in the effluent just after applying ultrasound treatment. The average values obtained in effluent just after exposing to ultrasound were 87+/-11 mg TCOD l^{-1}, 107+/-37 mg TCOD l^{-1} and 82+/-21 mg TCOD l^{-1}. Even for those conditions COD was below local discharge requirements of 150 mg l^{-1}.

During steady state conditions (data presented in Table 6.4(a)) no significant changes in measured influent and effluent COD was observed. For two lower dosages of ultrasound no change in both total and soluble COD was detected and values measured in the effluent were unchanged when compared to influent concentrations. Some increase in average total COD occurred at highest applied ultrasound dosage, however no statistically significant difference was observed (see Table 6.4). Also the comparison of the results in testing and control reactor showed no significant difference in total and soluble COD in effluents for first three phases of the experiment. The highest ultrasound dosage, which resulted in the most significant change in biofilm thickness, characterized with the increased effluent TCOD when compared to control conditions due to removal of organic solids.

Overall results suggest that no intensive cell rupture or EPS extraction occurred for the chosen dosage of ultrasound. Proper ultrasound treatment is thus able to improve MBfR performance without the risk of COD breakthrough.

6.3.7. Impact of different ultrasound dosages on membrane structure

The structural integrity of membrane fibers was monitored through the experiment. The measurements of hydrogen flow and pressure were carried out on daily basis in order to detect sudden changes resulting from possible damage of membrane due to exposure to ultrasound. The results show that increase in hydrogen flow occurred together with increased dosage of ultrasound. Figure 6.9 depicts the increase in hydrogen flow and pressure while exposing the MBfR to ultrasound. The fluctuations in hydrogen flow in reactor not exposed to ultrasound were minimal and equal to 2 ml min^{-1}. However

introduction of ultrasound treatment led to the following increase of 12, 15 and 23 ml min^{-1} in phases 2, 3 and 4 respectively.

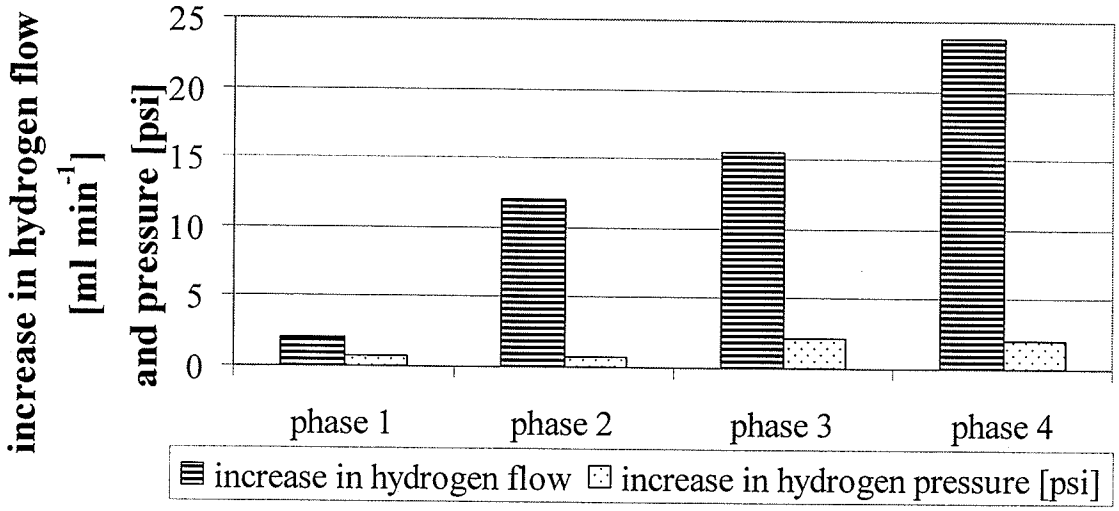


Figure 6.9 Fluctuations in hydrogen pressure and hydrogen flow during exposure of MBfR to ultrasound *Phase 1- no shear; Phase 2 – ultrasound treatment – 15 sec a day; Phase 3 – ultrasound treatment – 60 sec a day; Phase 4 – ultrasound treatment – 120 sec a day*

Changes in hydrogen flow were firstly attributed to changes in biofilm structure, especially thickness which occurred in fourth phase of the experiment. Further microscopic inspection of the membrane fibers showed that ultrasound treatment removed the mineral crust otherwise covering outer layers of the membrane fiber. The comparison of the fiber obtained from MBfR before and after exposing it to ultrasound treatment is presented on Figure 6.10. Lack of mineral precipitants composed of Ca, P, Fe, Mg, Si and K covering the fibers could contribute to better hydrogen diffusion.

The inspection of membrane fibers showed no damage to the membrane fibers for low and medium ultrasound dosages. Figure 6.11 show the membrane fibers after the ~ 40

days of exposure to ultrasound for 15 sec and 60 sec twice a day. The highest ultrasound dosage did not results in significant damage as structural integrity of majority of the fibers was untouched however few round wholes were detected during the microscopic observations. The damages are presented on Figure 6.12. The shape of the damage is consistent with previous observations that shear force created by ultrasound results mostly from collision of micro particles with membrane surface thus round shape holes (Wen at al., 2007).

Observed removal of mineral precipitants from the membrane surface and occasional damage of the fiber suggest that ultrasound penetrated through whole biofilm thickness. This confirms that careful choice of ultrasound dosage and continuous monitoring of MBfR during ultrasound treatment is necessary to prevent significant damage of the membrane.

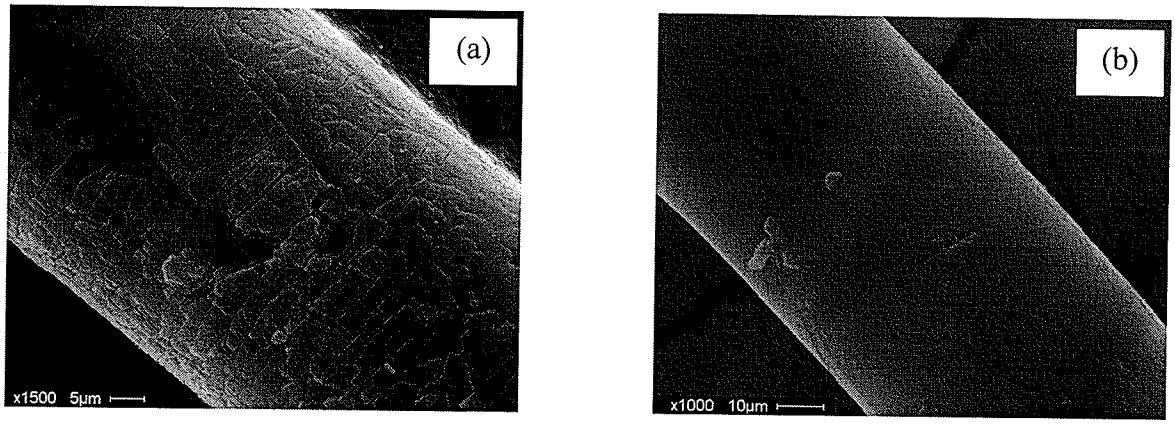


Figure 6.10 Fiber before (a) and after (b) exposing MBfR to ultrasound treatment

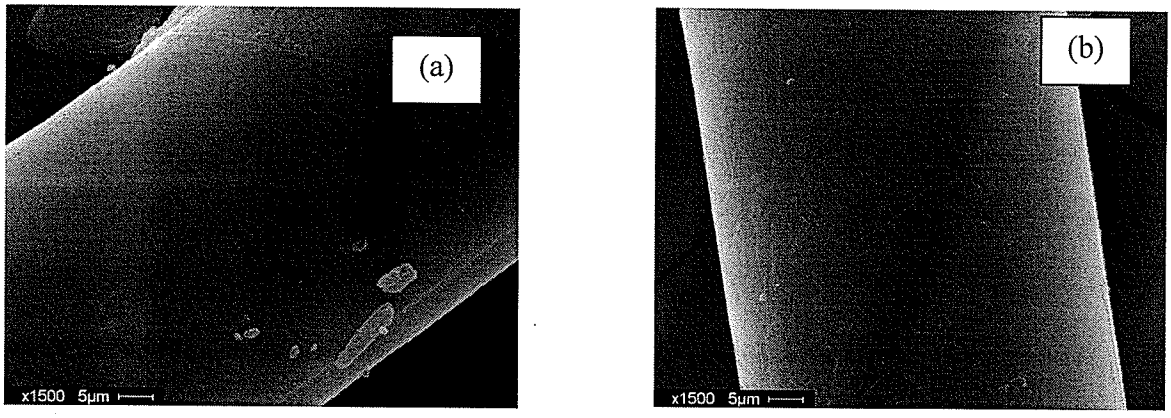


Figure 6.11 Membrane fiber after exposing to 15sec (a) and 60 sec (b) twice a day

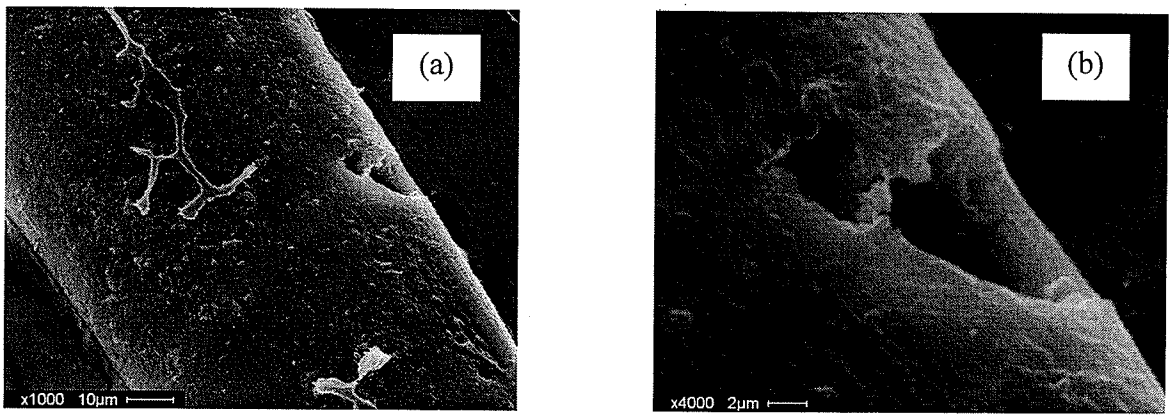


Figure 6.12 Damaged membrane fiber at x1000 (a) and x4000 (b) magnification

6.3.8. Hydrogen utilization efficiency

Hydrogen utilization is an important parameter which can be decisive for efficiency and economical feasibility of MBfR for hydrogenotrophic denitrification. The hydrogen utilization efficiency (HUE) was obtained from denitrification stoichiometry and varied between 14% and 46% (refer to Chapter 5, point 5.3.9.) however no correlation between ultrasound dosage and HUE could be determined. The results suggest that hydrogen utilization efficiency increased together with decrease in biofilm thickness (Table 6.3). Observed HUE was fairly low comparing to values presented by other researchers, which stated HUE close to 40% (Ergas and Reuss, 2001; Terada et al., 2006). The HUE

observed for MBfR systems with mixing and nitrogen sparging used as a shear force was also much higher and varied between 40% and 100%. Ultrasound treatment seems to minimize hydrogen utilization efficiency and thus can lead to increase in operational cost (increased cost of supplied electron donor).

6.4 CONCLUSIONS

The study demonstrated that ultrasound can be used to effectively control the biofilm structure and therefore performance of MBfRs. Based on experimental data the following specific conclusions were formulated:

1. Ultrasound treatment improved denitrification rates by reducing biofilm thickness and improving diffusion of substrates.

2. Operation without any shear force resulted in accumulation of biofilm and increase in its thickness up to approximately ~813 μm, while ultrasound treatment (> 60 sec/ 12 hours) decreased the thickness to approximately ~ 370 μm.

3. The highest average denitrification rates, equal to 1.12 gNO_3-N $m^{-2}d^{-1}$ were obtained for the highest dosage of ultrasounds tested.

4. Ultrasound dosages had no significant impact on biofilm density expressed by total and volatile solids content for treatments up to 120 sec/ 12 hours.

6. Small and medium dosage of ultrasound increases biofilm viability probably due to removal of excess dead cell in the beginning of each testing phase and due to continous shedding of biomass from biofilm. The highest dosage of ultrasound results in decrease in bacteria viability thus ultrasound dosage should be carefully chosen.

7. No significant sloughing of biomass (detachment of the large parts of biofilm) and COD breakthrough was observed during steady state conditions.

8. No significant damage of the membrane fibers was observed for lower dosage, however higher dosage may cause small defects in fibers structure.

CHAPTER 7: ENGINEERING SIGNIFICANCE

7.1 NECESSITY OF NO_3-N REMOVAL

Excess nitrogen and phosphorus content led to significant water quality problems including harmful algal blooms, hypoxia and declines in wildlife and wildlife habitat. Algal blooms can be harmful to human health as some of algae produced toxins can be stored by certain marine organism (shellfish, scallops) which are consumed by humans. It can also be harmful to fish farms and cause foaming. It has been observed that low nutrient concentrations, which can be obtained by good watershed management, stop excess algal blooms. The availability of light, size of the receiving water body, water flows, losses due to dilution are other, natural factors decisive for aquatic habitat health (Fretwell, 2006).

Three dimensional, coupled physical-biological models are required to properly analyze the risk of eutrophication. Some of the ecosystems are naturally eutrophic (richly in nutrients and aquatic life) while some are oligotrophic (poor in nutrients and pristine with little aquatic biomass) and thus are more susceptible to anthropogenic eutrophication i.e. the process that brings about the change in trophic state and leads to undesirable consequences (Tett and Edwards, 2002). The availability of nutrients, mainly nitrogen and phosphorus is the basis for creating these models. Specific analysis of local conditions is required to determine acceptable range of N: P ratio. Depending on the location, the suggested N:P ratio should be from 7:1 to 30:1(Tett and Edwards, 2002). It should be noted that besides high nutrients concentration, other suitable physical conditions or lack of grazing can cause algal blooms. Apparent fluctuations in

hypernutrition and eutrophication can result also from changes in the mixture of strains occurring in given algal population. Depletion of one of the nutrients relative to others (phosphorus vs. nitrogen) or change in the source of nutrient element (ammonium, nitrate vs. nitrogen gas) is known to cause:

- shift in population,
- physiological stress which increase cellular toxin content contributing to toxicity of algal blooms.

Limiting the discharged loading of both phosphorus and nitrogen seems to be vital way to protect the stability of water as increased nutrient input increases the risk of harmful effects from algal blooms. Plants, algae and photosynthetic bacteria, incorporate nitrate and phosphate dissolved in water into organic compounds during their growth. Sewage treatment that involves the removal of organic matter and phosphorus but does not involve nitrate removal can improve the oxygen level in receiving rivers. As such it also can decrease the nitrogen losses in rivers and estuaries due to denitrification, but at the same time leads to more eutrophication of coastal waters into which the rivers discharge (Billen et al., 1991).

7.2 TECHNOLOGICAL NECESSITY OF ADVANCED NITRATE REMOVAL

Adding a post- denitrification, i.e. denitrification as a tertiary treatment step (such as heterotrophic denitrification or hydrogenotrophic denitrification in MBfR) into biological nutrient removal process would cause significant change in the whole culture of BNR design. Some wastewater treatment plants in various cities such as Helsinki (Finland), Frankfurt (Germany), City of Tampa (Florida, USA), and Washington (USA) have

noticed that polishing of the final effluent is necessary in order to comply with local environmental policy requirements and protect especially sensitive waters. Effluent permits are often at less than 3 mg/L of total nitrogen. Conventional heterotrophic denitrification cannot deliver such performance. Addition of advanced wastewater treatment in tertiary mode is sometimes necessary however new treatment step needs to be technologically unfailing and economically feasible. Evaluation of the total capital and operating cost is necessary to determine the feasibility of any proposed new technology.

7.3 OBJECTIVES

This chapter focuses on evaluating the feasibility of polishing the final effluent from North End Water Pollution Control Center (NEWPCC). The insight into the contribution of the discharge from NEWPCC to pollution of the Red River and Lake Winnipeg is presented.

As Winnipeg's wastewater has low organic carbon concentrations, external electron donor needs to be supplied in order to achieve complete denitrification. Two different design alternatives for upgrading the current BOD removal plant are proposed. The designs differ based on the type of electron donor:

- the addition of methanol to stimulate heterotrophic denitrification (conventional system with activated sludge tank and settling tank, and system with Biostyr type carrier filters),
- the addition of H_2 (MBfR carrying autotrophic hydrogen - driven denitrification).

Detailed economic analysis of the different methods of controlling MBfR described in previous chapters will be carried out. The options are evaluated based on the cost and produced water quality.

7.4 NUTRIENT CONCENTRATION IN LAKE WINNIPEG AND RELATED THREAT OF EUTROPHICATION

The North End Wastewater Treatment Plant discharges its effluent into the Red River, located in the watershed of Lake Winnipeg. Lake Winnipeg is a large lake with surface area equal to 3.7% of Manitoba and supports fisheries, recreation, lakeshore communities and hydroelectric systems of the Province. The management of the Lake Winnipeg waters is very important for Manitoba and many attempts have been made to develop Nutrient Management Strategies. The drainage basin of the lake is second biggest in Canada (after Mackenzie River) thus many sources contribute to the yearly nutrient load that Lake Winnipeg receives. The analysis of Lake Winnipeg waters indicates that the south basin's water, located close to the mouth of the Red River has high nutrients concentrations suggesting significant role of Red River in polluting Lake Winnipeg's waters (North/South Consultants Inc., 2006). The nitrogen and phosphorus concentrations are several times higher in the southern than in the northern part of the lake. The nitrogen concentrations in south basin vary between 0.5-0.9 TN mg l^{-1} in spring to 0.6- 1.3 mg TN l^{-1} in summer. The spring and summer concentrations in the north basin are lower and equal to 0.4-0.5 mg TN l^{-1} and 0.4- 1.0 mg TN l^{-1} respectively. It is believed that the Red River supplies 46% of the nitrogen load to the lake and thus the improvement of the Red

River water quality is an important factor on the road to recovery of the class of Lake Winnipeg (North/South Consultants Inc., 2006).

The TN:TP ratio, which is believed to be the main indicator of water eutrophication has changed in past years suggesting changes occurring in the lake. The observations showed an increase in both TN and TP of anthropogenic origin. Even though in the south basin TN:TP remains close to 10:1 which defines nitrogen limitation, values reported for north basin increased to 10:1-20:1. The comparison of present values with the values of 6:1 (south basin) and 11:1 (north basin) obtained in 1969 show an increasing trend.

The addition of N has been found to increase phytoplankton concentrations by 2 to 4 times. Increase in algal abundance and occasional algal blooms were observed (chlorophylla at levels of 2 – 20 $\mu g\ l^{-1}$). The increase in water turbidity and decrease in oxygen concentration are eutrophication related changes in water quality. In 1969 the reported, summer dissolved oxygen concentrations were equal to 9.5-11 $mg\ l^{-1}$ while currently the oxygen values vary between 3.6 and 7.0 $mg\ l^{-1}$. The eutrophication of Lake Winnipeg leads to the reduction of biodiversity in the so called cascading effect. Unfortunately some of the researchers observed that improving water quality by reducing the nutrients concentrations does not always allow for the return to the initial water quality.

Nevertheless the removal of nitrate from wastewater and thus receiving natural waters is important as high levels of nitrate can have a number of negative for environment effects (Fretwell, 2000):

- at certain levels and during long exposure times nitrites can be lethal to fish or make them more susceptible to diseases and inhibits their ability to reproduce,

- at early life stages many aquatic animals are more sensitive to nitrate than are juvenile and adult animals. Larval stages of amphibians appear to be particularly sensitive to subtle effects of nitrate exposure,
- high levels of nitrate in lakes and coastal areas can therefore contribute to the excessive growth of plants and algae,
- an incomplete denitrification in natural waters can lead to N_20, a potent greenhouse gas.

7.5 COMPARISON OF HETEROTROPHIC AND AUTOTROPHIC DENITRIFICATION FOR POLISHING OF THE FINAL EFFLUENT

The heterotrophic and autotrophic hydrogen driven denitrification used for polishing step were evaluated for North End Water Pollution Control Centre in Winnipeg. Current system at NEWPCC provides screening, grit removal, primary sedimentation and activated sludge secondary treatment (Rezania, 2006). A polishing step targeting denitrification can be implemented after full COD, ammonia and phosphorus removal system thus following assumptions were made:

1. the polishing step follows systems with COD and ammonia (through nitrification) removal within oxidation tank,
2. the polishing step follows the system with phosphorus removal through chemical precipitation,
3. the quality of the effluent from the assumed system has been determined based on the results anticipated for the Winnipeg's municipal wastewater.

Table 7.1 presents the anticipated quality of the wastewater treated during the polishing step:

1. total and volatile suspended solids, as well as total and soluble COD were equal to current effluent quality,
2. nitrates concentration was based on the value obtained during full nitrification (ammonia concentration in Winnipeg's municipal wastewater is equal to ~ 30 mg l^{-1}),
3. phosphorus concentration was assumed as typical value for effluent after chemical precipitation,
4. pH and alkalinity were established basing on the predicted impact of nitrification.

Table 7.1 Estimated quality of the effluent before polishing step

Parameter	Concentration [mg l^{-1}]
Volatile suspended solids	~7
Total suspended solids	~9
Total COD	~23
Soluble COD	~13
Total P	~0.5- 1
Ammonia N	~0.5-1
Nitrate N	30
pH	~7.3
alkalinity	~197

7.5.1 Basic design of a heterotrophic, methanol driven denitrification in conventional system

The first evaluated alternative for polishing final effluent was heterotrophic denitrification carried out with externally supplied methanol in conventional system composed of activated sludge tank and settling tank. The basic design was carried out in order to determine approximate capital and operating cost and included the following:

- CAPITAL COST
  - additional reactors (assumed HRT = 2.5 hours, total volume 31 458m^3),
  - mixers,
  - methanol storage tanks (tank volume 50m^3, based on 14 days supply),
  - tertiary settling tank (assumed HRT= 2.8 hours, total volume),
- OPERATING COST
  - Power for mixing,
  - Power for pumping (internal recycle – 300%),
  - Methanol cost (2.47 g methanol/g NO_3-N removed).

The determined reactors dimensions are presented in Table 7.2.

Table 7.2 Designed parameters of activated sludge tank for methanol -driven denitrification of final effluent from NEWPCC

ADWF	m^3/d	302,000
# of reactors	-	8
Volume of each reactor	m^3	3932
Reactors dimensions	-	
length	m	52
width	m	25
depth	m	3

7.5.2 Basic design of a heterotrophic, methanol driven denitrification with Biostyr carrier

The second evaluated alternative for polishing final effluent was heterotrophic denitrification with a Biostyr carrier, stimulated with externally supplied methanol serving as an electron donor. In this method, the media acts as a filter for the physical removal of the suspended solids as well as provides adequate surface area for the

attachment of the biofilm. The media is composed of specially treated spherical polysterene beads covered by active biomass. Upon entering the filter the wastewater flows upward through the filter media. Growth of biomass and the retention of suspended solids in the filter media make periodic backwashing necessary. Backwash intervals typically vary from 24 to 72 hours and are triggered either when the head loss across the filter exceeds a pre-determined set point or when an operator adjustable time limit has expired. Effluent that collects in the common treated effluent reservoir flows down through the filter by gravity, causing the media to fluidize. The process air grid located below the media is used to supply scouring gas during the backwash sequence.

The basic design was carried out in order to determine approximate capital and operating cost and included the following:

- CAPITAL COST
  - additional filters,
  - Biostyr carrier,
  - methanol storage tanks (tank volume $50m^3$, based on 14 days supply),
  - backwash waste storage,
  - backwash gas ramp,
  - cell roof (to retain the carrier in the tank),
- OPERATING COST
  - Power for pumping (internal recycle – 300%, backwash),
  - Methanol cost (2.47 g methanol/g NO_3-N removed),
  - Power for gas sparging backwashing.

As the Biostyr system is patented only estimate cost of the system (without any details) could be obtained and such is presented in Table 7.6.

7.5.3 Basic design of MBfR for hydrogen driven denitrification

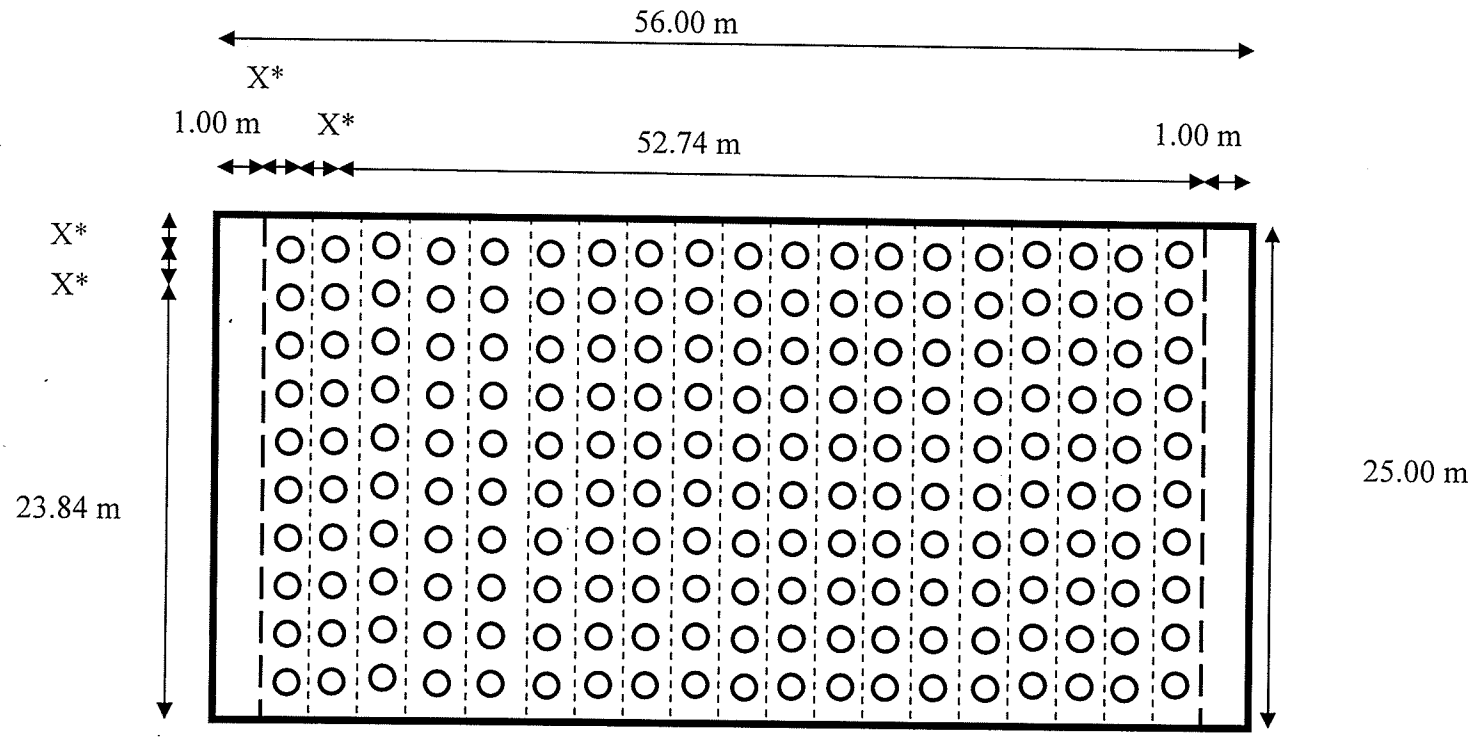
The other alternative for post denitrification was autotrophic hydrogen driven denitrification within MBfR. The basic schematic of MBfR (not to scale) is presented on Figure 7.1 (a) and (b). The determined MBfR dimensions are presented in Table 7.3. The HRT used during the testing period (4 hours) was also used as a base for calculations for the full scale system.

Table 7.3 Designed parameters of the MBfR for hydrogenotrophic denitrification of final effluent from NEWPCC

ADWF	m^3/d	302,000
# of reactors	-	12
Volume of each reactor	m^3	4194
Reactors dimensions	-	
length	m	56
width	m	25
depth	m	3

The necessary number of membranes varied depending on the evaluated option and was calculated based on removal efficiency obtained during the laboratory experiment expressed in gN $m^{-2}d^{-1}$. The dimensions of membranes to be used in full scale application were provided by manufacturer GE Water & Processes Technology – Zenon Membrane Solutions. The prototype membrane is manually produced and has following dimensions 0.25x0.25x2.15 m. With potting density of 25% provides 154m^2 of surface area. The Figure 7.2 presents the schema of the membrane. Suggested configuration could be different for automated production. Table 7.4 presents the number of membranes required for each following evaluated methods:

(a) horizontal



X* - the distance between membranes varies depending on the number of membranes different for altered operating regime

(b) vertical

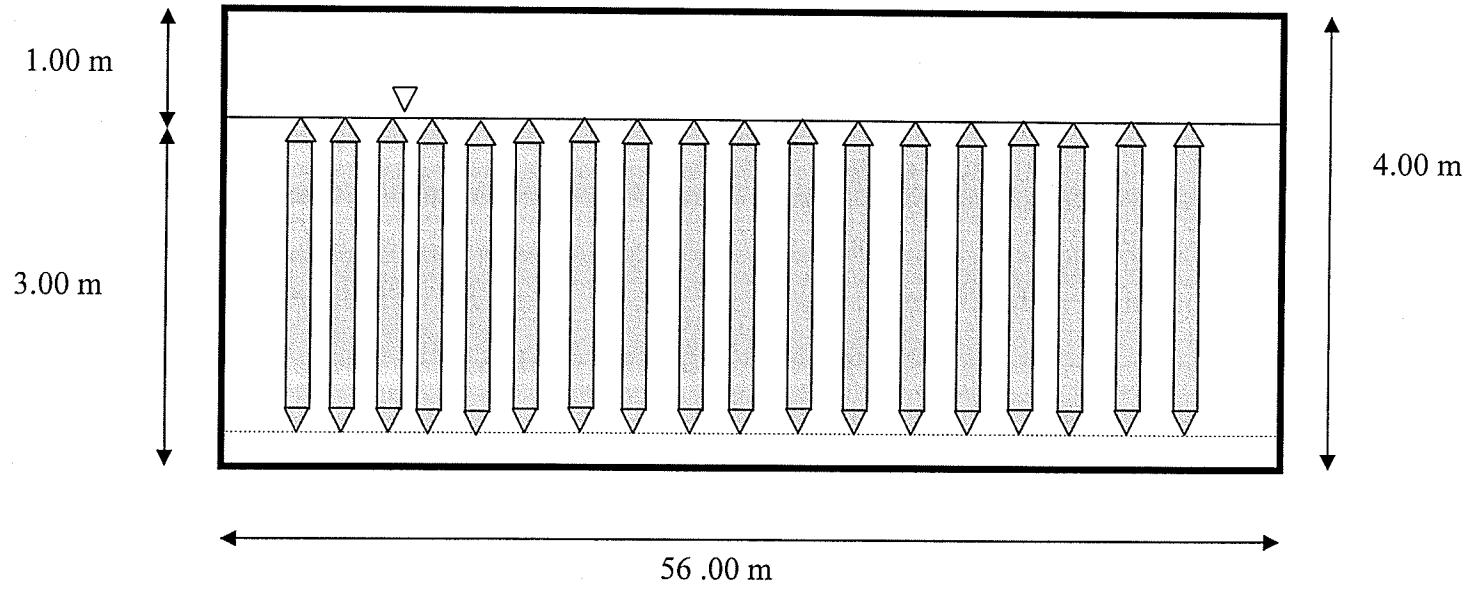


Figure 7.1 Schematic of the MBfR

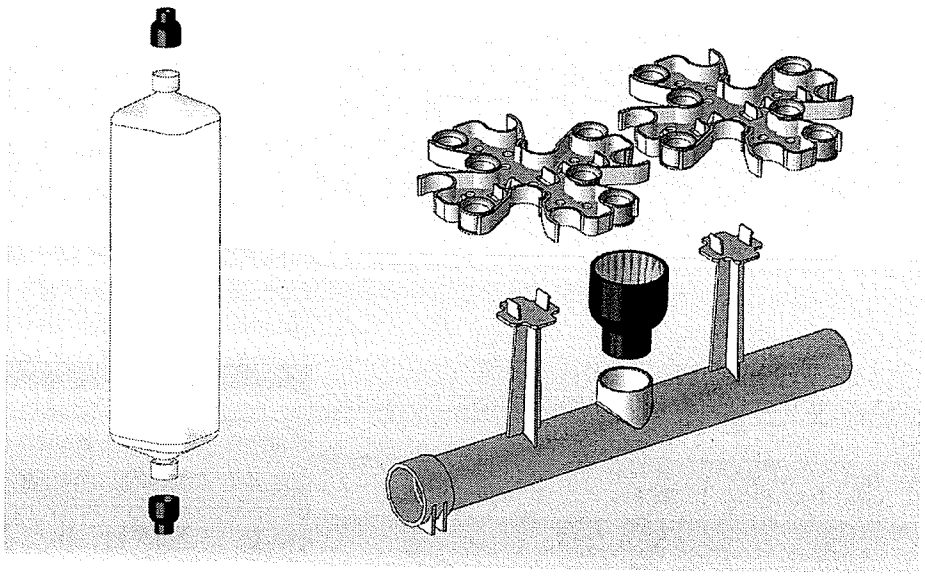


Figure 7.2 Schematic of the "prototype" membrane (provided by GE Water& Processes Technologies – Zenon Membrane Solutions)

- Hydrogenotrophic denitrification in MBfR controlled by hydrogen limitation,
- Hydrogenotrophic denitrification in MBfR controlled by mixing:
  - Low level of mixing (8 W/m^3),
  - Medium level of mixing (10 W/m^3),
  - High level of mixing (13 W/m^3),
- Hydrogenotrophic denitrification in MBfR controlled by mixing (13 W/m^3) and nitrogen sparging:
  - Low level of sparging (17 ml N_2/min/ L of reactor volume),
  - Medium level of sparging (50 ml N_2/min/ L of reactor volume),
  - High level of sparging (100 ml N_2/min/ L of reactor volume),
- Hydrogenotrophic denitrification in MBfR controlled by ultrasound treatment:
  - Low dosage of ultrasound,

- Medium dosage of ultrasound,
- High dosage of ultrasound.

Table 7.4 The number of membranes required for different operating modes

Operation based on	Removal rate [gN $m^{-2}d^{-1}$]	Required # of membranes	Distance between membranes X [m]
hydrogen limitation	0.58	101433	0.4
mixing			
low level of mixing	0.48	122565	0.36
medium level of mixing	0.51	115355	0.37
high level of mixing	0.63	93383	0.41
mixing&nitrogen sparging			
low level of nitrogen sparging	0.63	93383	0.41
medium level of nitrogen sparging	0.93	63259	0.5
high level of nitrogen sparging	0.93	63259	0.5
ultrasound			
low ultrasound dosage	0.68	86516	0.43
medium ultrasound dosage	0.80	73539	0.46
high ultrasound dosage	1.12	52528	0.56

Table 7.4 shows that the efficiency of the system at certain operating conditions affected the required number of membranes and as such contributed to overall cost of the systems. Basically, the higher the removal efficiency the lower the number of membrane and associated membrane cost.

7.5.4. The basis for capital and operating cost analysis of MBfR

The cost analysis included total capital cost and operational cost. Detailed description of the polishing treatment facilities for each evaluated methods is presented in Table 7.5.

Table 7.5 List of facilities for polishing treatment within MBfR

Hydrogen limitation	Mixing	Mixing & Nitrogen spraging	Ultrasound treatment
reactors ($4194m^3$ x 12)	reactors ($4194m^3$ x 12)	reactors ($4194m^3$ x 12)	reactors ($4194m^3$ x 12)
membranes *	membranes *	membranes *	membranes *
mixers **	mixers **	mixers **	ultrasound processors
		diffusers ***	
		pipeline for diffusers***	
		nitrogen blower & seal tank cover	

*number of membranes presented in Table 7.4

**number of mixers was determined basing on required power / m^3 of reactor

***number of diffusers and pipelines was based on required nitrogen flow

The MBfR controlled through hydrogen limitation and mixing was created as typical wastewater tank with membranes submerged within. The number and type of the mixers were determined based on the power input required for certain levels of mixing. The option with nitrogen sparging included sealed cover for the tank, additional diffusers systems (Airflex Cap 5" coarse bubbles diffusers) and blower (Omega G Series Gas Tight Blowers, Kaeser Compressors) to recycle the nitrogen from the tank's headspace. The numbers of diffusers, required pipelines and type as well as the number of blowers were determined basing on the nitrogen flow. The schematic of this reactor is presented on Figure 7.3.

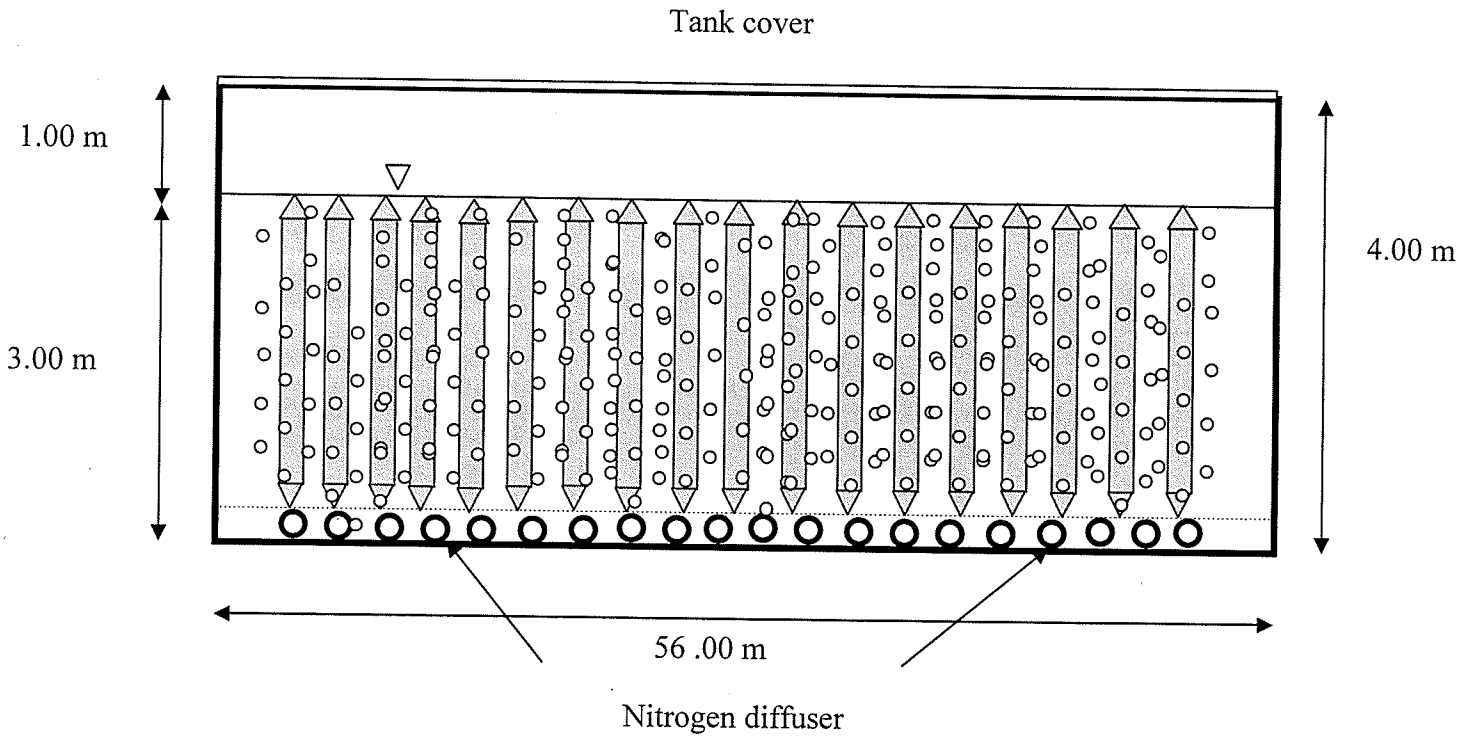


Figure 7.3 Schematic of MBfR diffusers system

The ultrasound application is new and there are no full scale applications so far. Thus the proposed design is purely theoretical and development in ultrasound devices manufacturing is required in order to apply this kind of treatment in a full scale system. The design aimed at providing even distribution of ultrasound waves within the reactors. The optimum solution seems to be using the device that resembles the ultrasonic cleaner and would provide one source of the ultrasound waves (preferably from the bottom of the tank). The other option was applying the number of ultrasonic processors which would be submerged within reactor. This type of probes are currently used for sludge disintegration and sold by few companies. Figure 7.4 presents the schema of the reactor with ultrasound processors.

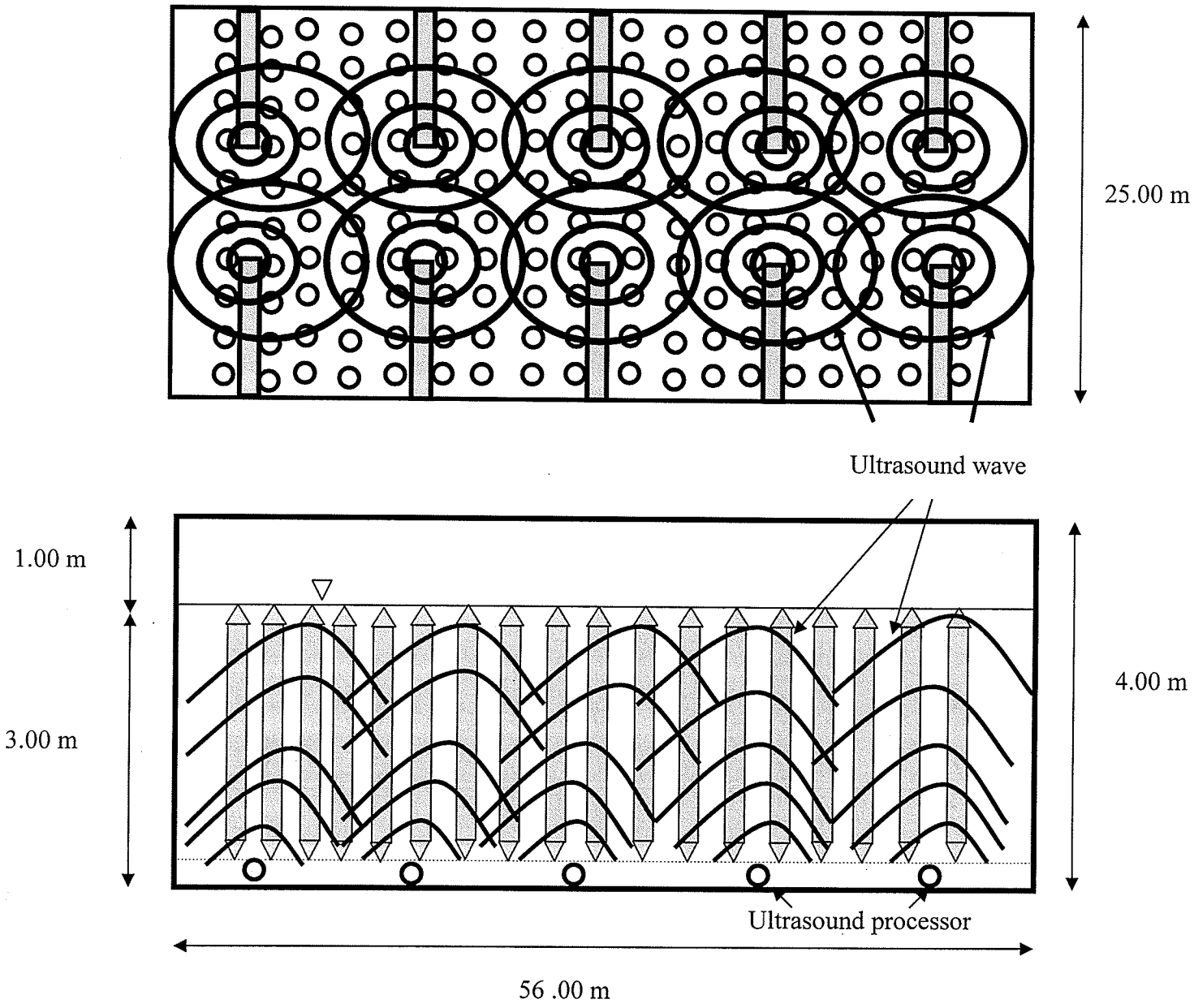


Figure 7.4 Schematic of MBfR with ultrasonic probes

Due to the laboratory design of the experiment (reactor was placed in ultrasound bath) the accurate required power input could not be determined. For that reason the actual required number of ultrasound processors could not be determined. Additional difficulty of the design based on ultrasound processors was associated with the application of two

or more sources of ultrasound (two or more ultrasonic probes) which can lead to superposition or interference of ultrasound waves. This phenomenon occurs when two or more waves meet and can lead either to cancelling or amplifying of the waves. The wave's amplification occurs when two waves with identical polarization, frequency, phase and amplitude meet and as the result increase in wave's amplitude is observed. The energy content of the waves is further directly proportional with the square of the amplitude thus double increase in wave's amplitude will caused 4 times higher energy content. The impact of ultrasound on the biofilm structure is believed to be caused by three main processes which are strongly related to the sonic field power. These processes are microstreaming within bacterial cells, resonance of the bacterial cells and chemical attack due to formation of radicals (Joyce et al., 2007). Resonance of bacterial cells as well as microstreaming increases with higher acoustic intensity as larger and more numerous cavitation bubbles form and amplitude of oscillation increases (Nyborg, 1982; Elder, 1959; Pitt and Ross, 2003). Radicals yield also increases with ultrasound power absorbed, to finally flatten out due to degassing of the solution (Mark et al., 1998). Superpositioning has to be taken into consideration in case of MBfR with many ultrasonic probes. The synergistic effect of multiple ultrasound waves can affect the required number of the ultrasonic processors by decreasing its number and thus significantly decrease the capital cost of this option. Further detailed research on the synergistic effect of the ultrasound should be carried out in order to provide accurate data regarding impact on MBfR and cost. Due to the above reasons the capital cost of ultrasound based system could not be determined and further data include only operating costs.

The operational costs were related to supplied hydrogen or methanol, energy consumption related to mixing and pumping, nitrogen supply with nitrogen blower and ultrasound treatment. The assumed process of hydrogen production is electrolysis with estimated cost of 1.37 \$/kg H_2 (50 kWh/ kg H_2). The analysis of possible revenue from the carbon credit was also introduced as it is already common practice within the UE and is planned to be introduced in North America. The MBfR system could produce the profits due to elimination of carbon dioxide emission otherwise occurring during the heterotrophic denitrification. The heterotrophic denitrification leads to emission of ~ 2.5 kg CO_2 (1 kg of NO_3-N)$^{-1}$ removed (Rezania, 2006). The revenue from carbon credit was calculated basing on UE carbon credit values equal to 37 \$ (ton of CO_2)$^{-1}$.

The N_2O gas emission, has not been related to any financial credit or fees, however it has been observed that N_2O emission during the heterotrophic denitrification contributes significantly to overall emission of this greenhouse gas (USEPA, 2008). It is believed that around 0.4% of reduced NO_3 is converted into N_2O (Tallec et al., 2008). The lower the C/NO_3 ratio the higher the emission of N_2O (Benckiser et al., 1996) and this relationship can be also used for hydrogen driven denitrification where H/NO_3 ratio will decide about the N_2O emission. It has been observed that pressure between 5 – 17 psi (1 psi= 6.8 kPa) depending on membrane used for hydrogen diffusion should lead to complete denitrification and eliminate any N_2O emission (Terada et al., 2006, Schnobrich et al., 2007).

7.5.5 Capital and operating cost of the system and present worth calculations

Based on actual construction experience for a wide range of wastewater treatment plants (AECOM, Stantec, CH_2MHill) the total capital cost includes cost for tankage and mechanical equipment (~70% of total capital cost) and site and electrical work (~30% of total capital cost). Thus total capital cost will be a calculated as the sum of these two expenditures. The total cost included total capital cost and operating cost of the system. The cost analysis was based on determining the present worth cost, which allows to bring life- cycle cost for a given time period for all candidate options to a common reference point for comparison. This method allows different options to be evaluated on an equal economic basis. This requires that all capital and operating costs be discounted to the base year based on the following equations.

Present Value for a single cash outflow in the future: $$PV = \frac{F}{(1+i)^n} \quad (7.1)$$

Present Value for a series of equal cash payments in the future: $$PV = A * \frac{(1+i)^n - 1}{i(1+i)^n} \quad (7.2)$$

Where:

F- single future payment, used for capital cost

A- equal annual payments into the futures, used for operating costs

n – the year the pay occurs, used for capital cost, base = 0

n- the number of years equal annual payments, used for operating costs, assumed 25 years

i – annual interest rate, assumed 6%

The detailed information on unit costs used for calculations can be found in the Appendix 2.

7.5.6 Evaluation of alternative for MBfR with hydrogenotrophic denitrification and heterotrophic denitrification

The design alternatives were compared in terms of cost and effluent quality. Nitrate, total and soluble COD as well as TSS and VSS were assumed as quality indicator and were estimated using the data from laboratory experiment. In terms of nitrate removal the MBfR system is able to provide similar quality of effluent due to possibility of adjustment of available surface area i.e. number of membranes. Hydrogen limitation allows for stable removal of NO_3-N. However, contrary to other tested methods, this operation mode eliminates the systems response to sudden fluctuations in nitrate concentration. All of tested methods were able to provide stable effluent with solids, total and soluble COD which were within required limits.

Table 7.6 presents the costs of the alternatives based on the formulas 7.1 and 7.2 and unit costs which are presented in detail in Appendix 2.

Table 7.6 Cost summary for considered options (30 mg NO_3 l^{-1})

	Total capital cost	Total annual operating cost	NPV operating cost (N=25, i=6%)	NPV capital and operating
Methanol application	55,369,818	5,231,506	66,876,203	122,246,021
Hydrogen limitation	68,252,557	1,424,803	18,213,768	86,466,326
Low level of mixing	72,641,258	4,634,490	59,244,335	131,885,593
Medium level of mixing	70,916,755	4,716,182	60,288,631	131,205,386
High level of mixing	66,037,585	3,944,652	50,425,886	116,463,471
High level of mixing + low nitrogen sparging	85,255,503	3,701,369	47,315,914	132,571,417
High level of mixing + medium nitrogen sparging	78,537,855	3,268,839	41,786,739	120,324,594
High level of mixing + high nitrogen sparging	80,437,792	3,271,423	41,819,760	122,257,552
Ultrasound treatment (low dosage)	NA	8,167,007	NA	NA
Ultrasound treatment (medium dosage)	NA	10,096,146	NA	NA
Ultrasound treatment (high dosage)	NA	4,230,378	NA	NA
Biostyr	121,887,878	5,102,891	65,232,068	187,119,946

Note: low, medium, high levels of mixing and nitrogen sparging, as well as low, medium and high dosage of ultrasound used for calculations were assumed as explained in chapter 5 and 6

The lowest capital cost was determined for option based on conventional, heterotrophic denitrification (~ $55 million) while the capital cost of MBfR and Biostyr filters was relatively higher. The increase in capital cost of MBfR was caused firstly by the cost of membranes and the total capital cost of this system would be around $ 13 million higher. The prices provided by the manufacturer GE Water & Processes Technology were based on manual production and automated manufacturing would most probably change the membrane price. Application of nitrogen sparging resulted in additional increase in capital cost due to spending for additional equipment such as diffusers, pipelines,

nitrogen blowers. This option would result in capital cost increase of around $20 million compared to a typical activated sludge and settling tank option with heterotrophic denitrification. The capital cost of Biostyr implementation was the most expensive and equal to $121 M due to cost of the filter tanks and Biostyr carrier. No data regarding the capital cost of the ultrasound treatment system could be provided due to reasons presented in Point 7.5.4.

The lowest operational cost was determined for the option based on hydrogen limitation (supplied hydrogen equal to 83% of required for total removal in order to maintain the concentration of nitrates in the effluent lower then 5 mg NO_3-N l^{-1}).

The benefit of using the MBfR could be also observed when annual operating cost of other MBfR system was analyzed. There is possibility of significant saving of ~ $2 M per year for a system operated with mixing and medium nitrogen sparging when compared with heterotrophic denitrification carried out both in conventional system as well as in Biostyr carrier filters. Additional operational cost associated with cost of mixing and nitrogen sparging was balanced by high hydrogen utilization rate and lower hydrogen cost as well as carbon credit. The operational cost of methanol driven denitrification carried out in conventional system comprised of relatively high cost of the electron donor and cost of sludge treatment and disposal. Cost of disposal of sludge at the landfill (equal to ~ $650 000 year) was assumed for the calculations as this method is cheaper then drying, incineration and does not require new facilities. The highest operational cost (between $4 M and $10 M annually) for ultrasound treatment was caused by relatively low hydrogen utilization and high cost of supplied electron donor.

The lowest NPV was obtained for the MBfR operated with intentional limitation in hydrogen supply ($86 M) however this operation mode eliminates the systems response to sudden fluctuations in nitrate concentration. The MBfR controlled by high level of mixing allowed for relatively low cost of $116 M due to high removal rates (i.e. low required surface area of membranes) and high hydrogen utilization rate which allowed keeping the operational capital cost low. The polishing treatment through heterotrophic denitrification within traditional activated sludge and settling tank was more expensive then two previous methods ($ 122 M). Other tested methods based on MBfR characterized with slightly higher yet similar NPV which suggest that long term operation of MBfR is beneficial over traditional system with heterotrophic, methanol driven denitrification. The NPV of Biostyr carrier system was the highest due to relatively high capital cost. The NPV for ultrasound based system could not be established due to lack of information on cost of ultrasonic probes however relatively high operating cost suggest that long term operation would not be economically advantageous.

7.6 CONCLUSIONS

The analysis of the cost of introducing tertiary treatment in order to remove the nitrates through either heterotrophic or autotrophic hydrogen driven denitrification showed that:

1. The hydrogenotrophic denitrification with limited supply of hydrogen has the lowest net present value of capital and operating costs ($86 M). The MBfR controlled by high level of mixing allowed for relatively low cost of $116 M due to high removal rates (i.e. low required surface area of membranes) and high hydrogen utilization rate which allowed keeping the operational and capital cost low.

2. The polishing treatment through heterotrophic denitrification within traditional activated sludge and settling tank was more expensive than two previous methods (NPV = $ 122 M).

3. NPV of other analyzed methods based on MBfR were comparable to conventionally heterotrophically denitrifying system and varied between $120 M and $132 M. Application of Biostyr carrier filters was the most expensive due to high capital cost ($187 M).

4. Upgrade involving the classical heterotrophic denitrification requires the lowest capital cost while application of MBfR with mixing and nitrogen sparging resulted in increase in capital cost due to the need for additional equipment such as diffusers, pipelines, nitrogen blowers.

5. Additional operational cost associated with mixing and nitrogen sparging in MBfRs was balanced by high hydrogen utilization rate and lower hydrogen cost as well as carbon credit. As a result, MBfR systems allowed for the possibility of significant savings in annual operating cost (~ $2 M per year) compared with heterotrophic denitrification.

6. The relatively high operating operational cost of conventional, methanol driven denitrification was primarily caused by expenses related to methanol supply and sludge treatment and disposal.

7. The highest operational cost (between $4 M and $10 M annually) for ultrasound treatment was caused by relatively low hydrogen utilization and high cost of supplied electron donor and made ultrasound treatment economically unattractive.

CHAPTER 8: CONCLUSIONS AND RECOMENDATIONS[6]

The results and conclusions obtained in this research come from experiments involving MBfR carrying out hydrogenotrophic denitrification. Autotrophic denitrification is especially interesting for treatment of low organic carbon streams. Hydrogen - driven denitrification in MBfR offers a number of the important advantages over heterotrophic denitrification, however, lack of the control over systems performance remains the main challenge. The objective of this research was to evaluate methods of controlling the structure of the biofilm and performance of the MBfR.

Limitation of the electron donor (e.g. hydrogen) was used as one of the possible method of controlling biofilm growth and N - removal rates obtained through denitrification. It was found that starvation conditions limit biofilm development and allow maintaining stable denitrification rates. Despite the availability of excess nitrates no significant growth of microorganisms was observed in both of the tested reactors. Large fluctuations were observed in measured total solids (TS) concentration within the biofilm. Increase in TS was caused either by precipitation of the buffer substances or an attachment of solids present in the incoming wastewater, which was the main drawback of this method. Application of carbon dioxide in the gaseous form was used as the pH control method in order to prevent minerals accumulation. Addition of CO_2 and maintaining lower pH proved to efficiently decrease the total solids content within the biofilm and prevent biomass sloughing. Denitrification rates obtained during this operating mode were stable

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and remained unchanged for synthetic (SWW) and real municipal wastewater (MWW) effluent, as well as through the fluctuations in the substrate (NO_3-N) concentration. The average denitrification rates were however relatively low (0.59+/- 0.04 gNO_3-N $d^{-1}m^{-2}$) compared to heterotrophic denitrification revealing other important disadvantage of the tested method.

Different mixing conditions and sparging reactors content with nitrogen gas were evaluated as methods of controlling biofilm accumulation without limiting substrate availability and removal rates. The application of shear force through mixing and sparging was found to minimize biofilm accumulation and increase denitrification rates. The results of simultaneous measurements of biofilm density suggest that together with increased shearing force and decrease in biofilm thickness, biofilm density increased. The density of the biofilm was still significantly lower than the values obtained in reactors operated under hydrogen limitation, mainly due to limited inert solids accumulation. The changes in biofilm structure allow obtaining higher removal rates (up to 0.93 +/- 0.14 gNO_3-N m^{-2} d^{-1} for 300 μm thick biofilm). Hydrodynamic shear force was a reliable and efficient tool for controlling biofilm structure and MBfR performance.

Ultrasound treatment was another method used for controlling MBfR performance as it is able to deagglomerate bacteria clusters and inactivate bacteria through a number of physical, mechanical and chemical effects arising from acoustic cavitations. It proved to be efficient in altering the biofilm structure and improving removal rates. The test confirmed that minimizing biofilm thickness is crucial to the efficiency of MBfR. Increasing ultrasound dosage gradually reduced biofilm thickness and increased denitrification rates up to 1.17+/- 0.11 gNO_3-N m^{-2} d^{-1}. It was found that ultrasound

treatment of tested dosages had no significant impact on the volatile solids concentration, but at high (120 sec two times per day) dosages, it can destabilize the biofilm matrix. High ultrasound dosages can also lead to drop in bacteria viability, thus, moderate (15 and 60 sec two times per day) dosages are recommended as they were found to increase bacteria viability within a biofilm, probably due to removal of excess dead cells. Unfortunately, application of ultrasound significantly diminished the hydrogen utilization rate (HUE) and values of 15 – 46% were observed. Application of mixing and nitrogen sparging used as a shear force resulted in much higher observed HUE (40% to 100%) which was due to simultaneous decrease in biofilm thickness and the increase in biofilm density. The decreased HUE can contribute to high operating cost of the system due to increased cost of H_2 supply.

The analysis of biofilm composition during this study showed that its content varied depending on substrate availability and biofilm thickness. No excess excreting of the EPS was observed during the experiment with limited hydrogen supply. Measurements of EPS concentration in the biofilm showed some correlation between biofilm thickness and EPS content. Results suggest that thin biofilms characterized with lower EPS content, while increase in biofilm thickness leads to EPS accumulation. The results suggest also that while hydrodynamic shear force can affect EPS content, ultrasound treatment does not affect EPS accumulation.

The analysis of protein and carbohydrates content within biofilm showed that applying hydrodynamic shear force lowered the carbohydrates to proteins (c/p) ratio due to limitation of carbohydrates content and thus contributed to increased stability of the biofilm structure. Contrary, ultrasound treatment minimized the protein content and led to

increase in c/p ratio which might lead to decreased biofilm stability and increase the risk of biomass sloughing, VSS and COD breakthrough in the effluent.

Experiments showed that controlling biofilm thickness, density and composition allows for a stable biofilm structure and prevents biomass from sloughing and COD breakthrough in the effluent. Proper VS/TS ratio above 0.25 assures stable structure even for high biofilm thicknesses and densities. While limitation of hydrogen did not result in the removal of extra solids from the system, hydrodynamic shear force, sparging reactors content with nitrogen and ultrasound treatment efficiently removed low levels of biomass from the biofilm surface on the continuous basis. For all tested methods, during steady-state conditions, effluent solids stabilized at levels consistently below 20 mg l^{-1}, which is lower than adopted in Winnipeg discharge limit of 30 mg TS l^{-1} from wastewater treatment plants and eliminates the necessity of solids treatment and disposal. Preventing biomass sloughing allowed also to control total COD detected in the effluent from MBfR. The values measured in the effluent during steady state conditions were in the range of 60-120 mg COD l^{-1} which is below discharge requirements of 150 mg l^{-1} (European Union requirements).

The analysis of the cost of introducing tertiary treatment in order to remove the nitrates through either heterotrophic or autotrophic hydrogen driven denitrification in MBfR showed that the hydrogenotrophic denitrification with limited supply of hydrogen has the lowest net present value (NPV) of capital and operating costs ($86 M). The MBfR controlled by high level of mixing allowed for relatively low NPV of $116 M due to high removal rates (i.e. low required surface area of membranes) and high hydrogen utilization rate which allowed keeping the operational cost low. This option would be recommended

as it combines good and stable effluent quality with low NPV of the created system. The polishing treatment through heterotrophic denitrification within traditional activated sludge and settling tank was more expensive then two previous methods (NPV = $ 122 M). NPV of other analyzed methods based on MBfR were comparable to heterotrophically denitrifying system and varied between $122M and $132 M.

The highest operational cost (between $4 M and $10 M annually) was determined for ultrasound treatment. It was caused by relatively low hydrogen utilization and high cost of supplied electron donor which made ultrasound treatment economically not attractive.

Future research should involve further studies on ultrasound treatment in the system based on ultrasound probes. Ultrasound treatment seemed to improve the bacteria efficiency not only due to minimizing the biofilm thickness. The results obtained during experiments with mixing, nitrogen sparging and ultrasound show the inversely proportional relationship between biofilm thickness and denitrification rate. Nevertheless, the increase of biofilm denitrification efficiency is faster in case of ultrasound application. The published hypothesis suggest that ultrasound improves diffusion of substrate within a biofilm due to improved transport through the cell membrane, increased microconvection from ultrasonic heating, ultrasonic vibrational interactions with bubbles (cavitation events), reduction of boundary layer thickness due to turbulence or microconvection or saturate available binding sites more rapidly (Carmen et al., 2004; Qian et al., 1996). This mechanism is still not clear and further studies to find detailed reasons of this phenomenon should be carried out.

Research should also include the analysis of the synergistic effect of the ultrasound waves for few ultrasound sources in order to determine its impact on the MBfR.

The reasons for decrease in hydrogen utilization during ultrasound treatment should be identified as it could improve the economical viability of this otherwise very promising method.

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APPENDIX 1 SHEAR FORCE DISTRIBUTION

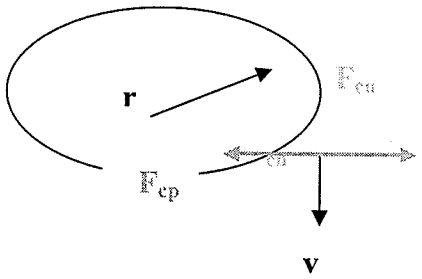
The shear stress caused by the flow around the submerged bodies can be calculated as:

Shear stress= τ = F/ A

Where: F – the acting force;

A – the surface area;

CENTRIFUGAL FORCE:



$$F_{cn} = mv^2/r$$

$$F_{cn} = m * \varpi^2 * r$$

Where: m – body mass [kg];

v – velocity [m/s];

r – radius [m];

ω – angular velocity [1/s].

The angular velocity of the particles moving in the distance equal to the stirring bar radius is equal to the angular velocity of the mixer. However the angular velocity of the particles in the vortex changes depending on the distance from its vertical axis of the vortex. According the Hemholtz statement the changes of the angular velocity are as follows:

$$A_1 * \varpi_1 = A_2 * \omega_2$$

$$\pi * r_1^2 * \varpi_1 = \pi * r_2^2 * \varpi_2$$

TABLE 1A Calculation for shear force distribution (100 rpm)

radius [m]	surface area [m^2]	angular velocity [1/s]	$\omega^2 * r$	m [kg]	force [N/m^2]
0.01	0.000314	1.67	0.027778	37.68	1.0466667
0.02	0.001256	0.42	0.003472	36.74	0.1275625
0.03	0.002826	0.19	0.001029	35.17	0.0361811
0.04	0.005024	0.10	0.000434	32.97	0.0143099
0.05	0.00785	0.07	0.000222	30.14	0.0066987
0.06	0.011304	0.05	0.000129	26.69	0.0034324
0.07	0.015386	0.03	0.000081	22.61	0.0018309
0.08	0.020096	0.03	0.000054	17.90	0.0009710
0.09	0.025434	0.02	0.000038	12.56	0.0004786
0.10	0.0314	0.02	0.000028	6.59	0.0001832

TABLE 1B Calculation for shear force distribution (150 rpm)

radius [m]	surface area [m^2]	angular velocity [1/s]	$\omega^2 * r$	m [kg]	force [N/m^2]
0.01	0.000314	2.50	0.0625	37.68	2.3550000
0.02	0.001256	0.63	0.00781	36.74	0.2870156
0.03	0.002826	0.28	0.00231	35.17	0.0814074
0.04	0.005024	0.16	0.00098	32.97	0.0321973
0.05	0.00785	0.10	0.00050	30.14	0.0150720
0.06	0.011304	0.07	0.00029	26.69	0.0077228
0.07	0.015386	0.05	0.00018	22.61	0.0041195
0.08	0.020096	0.04	0.00012	17.90	0.0021848
0.09	0.025434	0.03	0.00009	12.56	0.0010768
0.10	0.0314	0.03	0.00006	6.59	0.0004121

TABLE 1C Calculation for shear force distribution (300 rpm)

radius [m]	surface area [m^2]	angular velocity [1/s]	$\omega^2 * r$	m [kg]	force [N/m^2]
0.01	0.000314	5.00	0.25	37.68	9.4200000
0.02	0.001256	1.25	0.0313	36.74	1.1480625
0.03	0.002826	0.56	0.0093	35.17	0.3256296
0.04	0.005024	0.31	0.0039	32.97	0.1287891
0.05	0.00785	0.20	0.0020	30.14	0.0602880
0.06	0.011304	0.14	0.0012	26.69	0.0308912
0.07	0.015386	0.10	0.0007	22.61	0.0164781
0.08	0.020096	0.08	0.0005	17.90	0.0087393
0.09	0.025434	0.06	0.0003	12.56	0.0043073
0.10	0.0314	0.05	0.0003	6.59	0.0016485

APPENDIX 2 UNIT COST ESTIMATE CAPITAL AND OPERATING COST

TABLE 2A UNIT COST ESTIMATE CAPITAL COST

Item	Cost/unit	Units	Comments
Reactor	$9700(V)^{.66}$	m^3	V- required volume
Clarifiers	$16300(V)^{.65}$	m^3	V- required volume
Tank cover	$12910/ cover	cover	Thoro Shield 1850; nylon string reinforced coated vinyl; 185'/ 83' (56 /25 m)
Membrane	$204	membrane	manual production
Methanol tank	$87000/tank	$50m^3$	based on 14 days supply
Mixers	$8000/mixer	mixers	Aqua DDM Direct Drive Mixers; required # of mixers was determined basing on fluid vicosity, required horsepower (HP) per volume and HP of mixers; medium mixing = 100HP/ MG low mixing = medium mixing/2 high mixing= medium mixing*2
Nitrogen blower	$61348/ blower HB 950 , $77151/blower HB 1300PI, $88528/blower HB 1600PI	blower	Omega G Series Gas Tigth Blowers, Kaeser Compressors required # and model of blowers was determined basing on the required nitrogen flow, required psid and optimum parameters of blowers low level of N_2 sparging - blower HB950 medium level of N_2 sparging - blower HB1300PI high level of N_2 sparging - blower HB1600PI
Nitrogen diffusers	$7.15/diffuser	diffusers	Airflex Cap 5" coarse bubble diffuser; Aeration Store required # of diffusers was determined basing on the required nitrogen flow and optimum flow capacity of diffusers
Pipeline for nitrogen diffusers	$240/0.5m	4"PVC pipe	Aeration Store, pipeline with perforation for diffusers attachment
Ultrasound processors	200000/ ultrasonic probe UIP16000	ultrasound processor; for required power calculations	Hielscher, the model and # of the ultrasound processors was determined basing on the required power input per m^3 of reactor volume

TABLE 2.B UNIT COST ESTIMATE OPERATING COST

Item	Cost/unit	Units	Comments
methanol cost	0.53$/kg	kg of methanol	the required methanol and related cost was calculated basing on demand of 2.47 g methanol/ gNO_3-N
hydrogen cost	1.37$/kg	kg of hydrogen	production from electrolysis the required hydrogen and related cost was calculated basing on demand of 0.42 g methanol/ gNO3-N
electricity cost	0.0273$/kWh	kWh by Manitoba Hydro	http://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/current_rates.shtml#generallarge
sludge treatment and disposal	0.20$/kg$NO_3$-N		landfill application

TABLE 2.C POWER REQUIREMENTS FOR DIFFERENT OPERATING MODES

	Power requirements	Comments
power for mixing	0.013 kWh/m^3	low level of mixing
	0.010 kWh/m^3	medium level of mixing
	0.008 kWh/m^3	high level of mixing
power for nitrogen	55 kWh/blower	low level of nitrogen sparging
	77.5 kWh/blower	medium level of nitrogen sparging
	103 kWh/blower	high level of nitrogen sparging
power for ultrasound	12.5 kW/m3	the ultrasound dosage was varied basing on the time of the exposure

TABLE 2.D DETAILED SUMMARY OF THE CAPITAL AND OPERATING COSTS FOR DIFFERENT POLISHING ALTERNATIVES

	Total mechanical cost	Site works& electrical allowance	Total capital cost	Total annual operating cost	NPV operating cost (N=25, i=6%)	NPV capital and operating
Methanol application	41,014,680	14,355,138	55,369,818	5,231,506	66,876,203	122,246,021
Hydrogen limitation	50,557,450	17,695,107	68,252,557	1,424,803	18,213,768	86,466,326
Low level of mixing	53,808,339	18,832,919	72,641,258	4,634,490	59,244,335	131,885,593
Medium level of mixing	52,530,930	18,385,825	70,916,755	4,716,182	60,288,631	131,205,386
High level of mixing	48,916,730	17,120,855	66,037,585	3,944,652	50,425,886	116,463,471
High level of mixing + low nitrogen sparging	63,152,224	22,103,279	85,255,503	3,701,369	47,315,914	132,571,417
High level of mixing + medium nitrogen sparging	58,176,189	20,361,666	78,537,855	3,268,839	41,786,739	120,324,594
High level of mixing + high nitrogen sparging	59,583,550	20,854,242	80,437,792	3,271,423	41,819,760	122,257,552
Ultrasound treatment (low dosage)	NA	NA	NA	8,167,007	104,401,764	NA
Ultrasound treatment (medium dosage)	NA	NA	NA	10,096,146	129,062,624	NA
Ultrasound treatment (high dosage)	NA	NA	NA	4,230,378	54,078,425	NA
Biostyr	NA	NA	121,887,878	5,102,891	65,232,068	187,119,946

APPENDIX 3 RAW DATA

Table 3.A Removal rates obtained during experiment with flat sheet membrane module (experiment 1; Chapter 3)

	Operational conditions	Removal rates	pH	temperature
Cycle #	-	g NO_3-N $d^{-1}m^{-2}$	-	°C
1	mixing	0.37		
2	mixing	0.86		
3	mixing	1.25	7.36	27.3
4	mixing	1.01	7.31	28.0
5	mixing	0.59	7.38	28.3
6	mixing	1.06	7.41	28.3
7	mixing	1.08	7.48	28.7
8	mixing	1.00	7.39	28.3
9	mixing	1.02	7.23	27.7
10	mixing	0.90	7.27	28.0
11	mixing	1.00	7.28	27.8
12	mixing	1.14	7.26	28.0
13	mixing	1.07	7.29	28.2
14	mixing	0.96	7.26	27.8
15	mixing	1.00	7.20	28.0
16	mixing	0.99	7.26	27.2
17	mixing	1.01	7.38	27.3
18	mixing	0.98	7.44	26.3
19	mixing	1.00	7.42	26.3
20	mixing	1.11	7.31	26.8
21	mixing+ high oxygen concentration	0.96	7.45	26.7
22	mixing+ high oxygen concentration	0.91	7.45	27.3
23	mixing	1.09	7.23	26.8
24	mixing	1.10	7.25	25.9
25	mixing	1.01	7.12	26.3
26	mixing	1.24	7.21	26.0
27	mixing	1.15	7.20	26.6
28	mixing	0.68	7.28	26.2
29	mixing	0.71	7.14	24.3
30	mixing	0.64	7.24	24.7
31	mixing	1.18	7.24	25.8
32	mixing	1.16	7.00	23.8
33	mixing	1.20	7.22	26.5
34	mixing	1.16	7.28	28.3
35	mixing	1.17	7.27	27.8
36	mixing	0.97	7.37	27.4
37	mixing	1.00	7.28	26.1
38	mixing	1.05	7.25	26.3

39	mixing	1.03	7.19	26.8
40	mixing	1.13	7.18	26.5
41	lack of mixing	0.82	7.16	24.9
42	lack of mixing	0.68	7.14	23.6
43	lack of mixing	0.66	7.24	23.3
44	lack of mixing	0.50	7.24	24.3
45	mixing	0.93	7.10	25.2
46	mixing	0.93	7.07	24.0
47	mixing	0.93	7.12	24.7
48	mixing	0.99	7.14	25.7
49	mixing+ high oxygen concentration	0.77	7.20	25.2
50	mixing+ high oxygen concentration	0.91	7.20	24.3
51	mixing+ high oxygen concentration	1.02	7.20	24.3
52	mixing+ high oxygen concentration	0.92	7.17	24.0
53	mixing+ high oxygen concentration	0.85	7.20	24.7

Table 3.B pH, temperature and DO detected during the experiment with flat sheet module (experiment 1; Chapter 3)

Date	Operational conditions	Cycle #	pH	temperature [°C]	DO [mg O_2 l^{-1}]
30.06.2004	mixing	1	7.10	24	-
31.06.2004	mixing		7.08	28	-
01.07.2004	mixing		7.25	29	-
02.07.2004	mixing	2	7.38	30	-
03.07.2004	mixing		7.45	29	-
04.07.2004	mixing		7.67	29	-
05.07.2004	mixing		7.78	28.5	-
06.07.2004	mixing		7.79	28.5	-
06.07.2004	mixing	3	7.22	25	-
07.07.2004	mixing		7.33	28	-
08.07.2004	mixing		7.52	29	-
09.07.2004	mixing		7.63	29	-
09.07.2004	mixing	4	7.27	25.5	-
10.07.2004	mixing		7.27	29	-
11.07.2004	mixing		7.40	29.5	-
12.07.2004	mixing		7.47	30	-
12.07.2004	mixing	5	7.19	26	-
13.07.2004	mixing		7.42	29	-
14.07.2004	mixing		7.52	30	-
15.07.2004	mixing		7.53	28.5	-
15.07.2004	mixing	6	7.21	27	-
16.07.2004	mixing		7.49	29	-
17.07.2004	mixing		7.54	29	-
18.07.2004	mixing		7.59	28.5	-
18.07.2004	mixing	7	7.41	26	-
19.07.2004	mixing		7.49	30	-
20.07.2004	mixing		7.54	30	-
21.07.2004	mixing		7.59	30	-
21.07.2004	mixing	8	7.3	27	-
22.07.2004	mixing		7.32	29.5	-
23.07.2004	mixing		7.54	28.5	-
24.07.2004	mixing		7.58	28	-
24.07.2004	mixing	9	7.15	25	-
25.07.2004	mixing		7.23	29	-
26.07.2004	mixing		7.31	29	-
27.07.2004	mixing		7.41	29	-
27.07.2004	mixing	10	7.18	26	-
28.07.2004	mixing		7.25	29	-
29.07.2004	mixing		7.39	29	-

30.07.2004	mixing		7.44	29	-
30.07.2004	mixing	11	7.17	26	-
31.07.2004	mixing		7.27	28.5	-
01.08.2004	mixing		7.4	29	-
02.08.2004	mixing		7.48	29	-
02.08.2004	mixing	12	7.15	26	-
03.08.2004	mixing		7.24	28.5	-
04.08.2004	mixing		7.4	29.5	-
05.08.2004	mixing		7.47	29	-
05.08.2004	mixing	13	7.19	25.5	-
06.08.2004	mixing		7.27	29	-
07.08.2004	mixing		7.41	30	-
08.08.2004	mixing		7.51	29.5	-
08.08.2004	mixing	14	7.21	26.5	-
09.08.2004	mixing		7.27	29	-
10.08.2004	mixing		7.29	28	-
11.08.2004	mixing		7.39	27.5	-
11.08.2004	mixing	15	7.12	28.6	-
12.08.2004	mixing		7.24	27	-
13.08.2004	mixing		7.24	28.5	-
14.08.2004	mixing		7.4	28	-
14.08.2004	mixing	16	7.16	25	-
15.08.2004	mixing		7.23	28	-
16.08.2004	mixing		7.38	28.5	-
17.08.2004	mixing		7.51	29	-
17.08.2004	mixing	17	7.27	25.5	-
18.08.2004	mixing		7.41	28.5	-
19.08.2004	mixing		7.46	28	-
20.08.2004	mixing		7.5	27.5	-
20.08.2004	mixing	18	7.29	24.5	-
21.08.2004	mixing		7.42	27	-
22.08.2004	mixing		7.61	27.5	-
23.08.2004	mixing		7.77	27.5	-
23.08.2004	mixing	19	7.35	24.5	4.5
24.08.2004	mixing		7.44	27	3.1
25.08.2004	mixing		7.46	27.5	2.5
26.08.2004	mixing		7.57	28	2
26.08.2004	mixing	20	7.18	25	4.1
27.08.2004	mixing		7.31	27.5	1.9
28.08.2004	mixing		7.43	27.75	1.7
29.08.2004	mixing		7.49	27.75	1.5
29.08.2004	mixing+ high oxygen concentration	21	7.37	24.75	2.1
30.08.2004	mixing+ high oxygen concentration		7.47	27.5	2.1
31.08.2004	mixing+ high oxygen concentration		7.52	27.75	1.6

01.09.2004	mixing+ high oxygen concentration		7.56	27.75	1.2
01.09.2004	mixing+ high oxygen concentration	22	7.39	25	7.1
02.09.2004	mixing+ high oxygen concentration		7.43	28	4
03.09.2004	mixing+ high oxygen concentration		7.53	29	5
04.09.2004	mixing+ high oxygen concentration		7.57	29	5
04.09.2004	mixing	23	7.11	25	7.1
05.09.2004	mixing		7.24	27.5	5.2
06.09.2004	mixing		7.34	28	4.3
07.09.2004	mixing		7.44	27.5	4
07.09.2004	mixing	24	7.15	24.5	6.8
08.09.2004	mixing		7.29	26.5	4.5
09.09.2004	mixing		7.32	26.75	4.2
10.09.2004	mixing		7.39	27.5	2.6
10.09.2004	mixing	25	6.98	25	6.4
11.09.2004	mixing		7.14	27	3.7
12.09.2004	mixing		7.25	27	3
13.09.2004	mixing		7.34	27.5	2.6
13.09.2004	mixing	26	7.07	24	7.6
14.09.2004	mixing		7.18	27	3
15.09.2004	mixing		7.39	27	3.4
16.09.2004	mixing		7.4	27	2.7
16.09.2004	mixing	27	7	24	6.7
17.09.2004	mixing		7.14	26	3.2
18.09.2004	mixing		7.28	28	3.3
19.09.2004	mixing		7.39	28.25	2.8
19.09.2004	mixing	28	7.17	24.5	5.8
20.09.2004	mixing		7.25	26	0.9
21.09.2004	mixing		7.31	26	1.2
22.09.2004	mixing		7.32	25	0.4
22.09.2004	mixing	29	7.06	24	5.5
23.09.2004	mixing		7.12	24.5	1.7
24.09.2004	mixing		7.23	24.5	0.4
25.09.2004	mixing		7.42	25	0.2
25.09.2004	mixing	30	7.14	24	6.4
26.09.2004	mixing		7.22	25	3.5
27.09.2004	mixing		7.37	25	0.9
28.09.2004	mixing		7.39	25	0.7
28.09.2004	mixing	31	6.96	23.75	6.4
29.09.2004	mixing		7.2	26.75	4.1
30.09.2004	mixing		7.39	27.75	3.6
1.10.2004	mixing		7.49	26.75	2.9
1.10.2004	mixing	32	7	23.75	6.2
4.10.2004	mixing		7.56	26	2.3
4.10.2004	mixing	33	7.22	26.5	5.6

7.10.2004	mixing		7.55	27.5	1.7
7.10.2004	mixing	34	7.2	24.5	6.8
8.10.2004	mixing		7.28	28	2.8
9.10.2004	mixing		7.37	28.5	2.3
10.10.2004	mixing		7.52	28.5	1.6
10.10.2004	mixing	35	7.15	24.75	6.9
11.10.2004	mixing		7.27	29	2.9
12.10.2004	mixing		7.4	29.75	2.3
13.10.2004	mixing		7.51	29.75	2.3
13.10.2004	mixing	36	7.2	26	6.3
14.10.2004	mixing		7.41	27.75	3.3
15.10.2004	mixing		7.5	28.5	3.3
16.10.2004	mixing		7.61	28	3.1
16.10.2004	mixing	37	6.97	24.75	6.9
17.10.2004	mixing		7.37	27	4
18.10.2004	mixing		7.49	26.5	3
19.10.2004	mixing		7.53	27	2.7
19.10.2004	mixing	38	7.01	24	6.7
20.10.2004	mixing		7.24	27	3.4
21.10.2004	mixing		7.49	28	2.5
22.10.2004	mixing		7.56	28	2.3
22.10.2004	mixing	39	6.93	24.75	6.6
23.10.2004	mixing		7.23	27.5	3.9
24.10.2004	mixing		7.4	28	3.5
25.10.2004	mixing		7.53	27	2.7
25.10.2004	mixing	40	6.96	24	7.4
26.10.2004	mixing		7.24	27.5	4.1
27.10.2004	mixing		7.33	28	3.4
28.10.2004	mixing		7.44	28	2.9
28.10.2004	lack of mixing	41	7	24.75	6.8
29.10.2004	lack of mixing		7.2	25	3.9
30.10.2004	lack of mixing		7.27	25	1.4
31.10.2004	lack of mixing		7.34	24	0.1
31.10.2004	lack of mixing	42	6.98	23	6.3
1.11.2004	lack of mixing		7.18	23.75	2.5
2.11.2004	lack of mixing		7.26	24	1.8
3.11.2004	lack of mixing		7.37	23	0.9
3.11.2004	lack of mixing	43	7.14	22.5	6.6
4.11.2004	lack of mixing		7.28	23.5	1.6
5.11.2004	lack of mixing		7.3	24	1.3
6.11.2004	lack of mixing		7.33	24.5	0.8
6.11.2004	lack of mixing	44	7.18	23.75	7.3
7.11.2004	lack of mixing		7.27	24.5	2.8
8.11.2004	lack of mixing		7.28	24.5	2.3

9.11.2004	lack of mixing		7.31	24	1.4
9.11.2004	mixing	45	6.93	23	6.9
10.11.2004	mixing		7.14	26.5	4.2
11.11.2004	mixing		7.24	26	4
12.11.2004	mixing		7.33	26	3.6
12.11.2004	mixing	46	6.88	22	7.8
13.11.2004	mixing		7.12	25	4.1
14.11.2004	mixing		7.2	25	4.2
15.11.2004	mixing		7.34	25	4.2
15.11.2004	mixing	47	6.91	22	8
16.11.2004	mixing		7.2	25	4.4
17.11.2004	mixing		7.26	27	2.7
18.11.2004	mixing		7.28	27	3.1
18.11.2004	mixing	48	6.94	24	7.8
19.11.2004	mixing		7.18	26	4.1
20.11.2004	mixing		7.29	27	4
21.11.2004	mixing		7.43	26	4
21.11.2004	mixing+ high oxygen concentration	49	7.05	23.5	8.3
22.11.2004	mixing+ high oxygen concentration		7.22	26	4.6
23.11.2004	mixing+ high oxygen concentration		7.32	26	4.3
24.11.2004	mixing+ high oxygen concentration		7.39	26	3.7
24.11.2004	mixing+ high oxygen concentration	50	7.06	23	7.3
25.11.2004	mixing+ high oxygen concentration		7.22	25	4.5
26.11.2004	mixing+ high oxygen concentration		7.33	25	4.3
27.11.2004	mixing+ high oxygen concentration		7.38	25.5	3.8
27.11.2004	mixing+ high oxygen concentration	51	7.07	22.5	7.8
28.11.2004	mixing+ high oxygen concentration		7.18	25.5	4.4
29.11.2004	mixing+ high oxygen concentration		7.34	25	4
30.11.2004	mixing+ high oxygen concentration		7.4	25.5	3.8
30.11.2004	mixing+ high oxygen concentration	52	7.03	22	7.7
1.12.2004	mixing+ high oxygen concentration		7.15	25	4.5
2.12.2004	mixing+ high oxygen concentration		7.32	25	4.3
3.12.2004	mixing+ high oxygen concentration		7.42	25	3.9
3.12.2004	mixing+ high oxygen concentration	53	7.09	22	7.9
4.12.2004	mixing+ high oxygen concentration		7.17	26	4.5
5.12.2004	mixing+ high oxygen concentration		7.34	26	4.1
6.12.2004	mixing+ high oxygen concentration		7.47	25	3.7

Table 3.C TSS and VSS values in influent and effluent of batch system with flat sheet module (experiment 1; Chapter 3)

	TSS	[g l^{-1}]	VSS	[g l^{-1}]	VSS/TSS	VSS/TSS
day	Feeding	wasting	feeding	wasting	feeding	wasting
2	0.56		0.23		0.41	
8	0.16	0.23	0.02	0.07	0.12	0.30
11	0.15	0.22	0.04	0.03	0.27	0.14
14	0.26	0.24	0.07	0.07	0.27	0.29
17	0.07	0.12	0.05	0.06	0.62	0.51
20	0.04	0.03	0.03	0.01	0.61	0.45
23	0.05	0.04	0.01	0.01	0.21	0.25
26	0.05	0.06	0.01	0.02	0.21	0.24
29	0.03	0.02	0.01	0.01	0.29	0.59
32	0.06	0.02	0.02	0.02	0.42	0.87
35	0.10	0.03	0.03	0.01	0.27	0.22
38	0.05	0.03	0.03	0.03	0.63	0.88
41	0.10	0.11	0.03	0.03	0.31	0.33
47	0.08	0.08	0.02	0.02	0.29	0.27
50	0.05	0.04	0.01	0.01	0.15	0.22
53	0.06	0.07	0.02	0.02	0.38	0.31
56	0.04	0.07	0.01	0.02	0.25	0.27
59	0.07	0.06	0.03	0.04	0.40	0.62
62	0.06	0.08	0.01	0.05	0.19	0.60
65	0.05	0.06	0.02	0.03	0.31	0.41
68	0.04	0.09	0.01	0.03	0.17	0.30
71	0.05	0.07	0.02	0.03	0.33	0.39
74	0.04	0.06	0.02	0.03	0.50	0.51
77	0.11	0.08	0.03	0.03	0.23	0.31
80	0.06	0.06	0.03	0.03	0.54	0.56
83	0.05	0.07	0.02	0.02	0.33	0.27
86	0.04	0.06	0.01	0.02	0.28	0.27
89	0.04	0.06	0.01	0.01	0.20	0.20
92	0.05	0.06	0.01	0.02	0.32	0.25
95	0.10	0.04	0.03	0.01	0.30	0.19
98	0.06	0.03	0.02	0.01	0.30	0.23
101	0.08	0.04	0.01	0.00	0.19	0.07
104	0.05	0.05	0.01	0.01	0.14	0.15
107	0.05	0.06	0.02	0.02	0.33	0.40
110	0.05	0.07	0.01	0.02	0.31	0.29
113	0.05	0.03	0.02	0.02	0.44	0.52
116	0.04	0.06	0.01	0.02	0.32	0.39
119	0.03	0.06	0.01	0.02	0.31	0.34
122	0.05	0.04	0.02	0.02	0.37	0.47
125	0.02	0.07	0.00	0.02	0.22	0.31
128	0.03	0.06	0.00	0.02	0.00	0.38
131	0.01	0.03	0.01	0.00	0.63	0.09
134	0.01	0.02	0.00	0.00	0.29	0.11
137	0.05	0.02	0.02	0.02	0.35	0.68

140	0.06	0.04	0.03	0.03	0.41	0.72
143	0.05	0.08	0.01	0.02	0.15	0.21
146	0.03	0.04	0.00	0.00	0.09	0.13
149	0.03	0.05	0.01	0.01	0.26	0.23
152	0.03	0.04	0.01	0.01	0.33	0.36
155	0.04	0.07	0.01	0.01	0.24	0.20
158	0.05	0.06	0.01	0.01	0.21	0.24
161	0.05	0.05	0.01	0.01	0.15	0.21
164	0.08	0.05	0.02	0.01	0.22	0.15
167	0.08	0.08	0.01	0.02	0.08	0.22

Table 3.D Thickness, density (TS and VS content) and VS/TS ratio of biofilm created on flat sheet module (experiment 1; Chapter 3)

Date	Day of the experiment	Average biofilm thickness [μm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS
26.08.2004	59	500	285	130	0.46
		595	276	112	0.41
	average	**548**	**281**	**121**	**0.43**
	st.dev	**67**	**6**	**13**	**0.43**
2.09.2004	66	667	244	64	0.26
		625	250	60	0.24
	average	**646**	**247**	**62**	**0.25**
	st.dev	**29**	**4**	**3**	**0.02**
7.09.2004	71	1143	210	65	0.31
		476	235	85	0.36
		893	440	120	0.27
	average	**837**	**295**	**90**	**0.31**
	st.dev	**337**	**126**	**28**	**0.04**
13.09.2004	77	556	113	43	0.38
		688	109	40	0.37
		333	215	105	0.49
	average	**525**	**146**	**63**	**0.41**
	st.dev	**179**	**60**	**37**	**0.07**
21.09.2004	85	857	83	40	0.48
		714	170	80	0.47
		408	135	60	0.44
	average	**660**	**129**	**60**	**0.47**
	st.dev	**229**	**44**	**20**	**0.02**
27.09.2004	91	857	60	27	0.44
		833	85	20	0.24
		556	170	80	0.47
	average	**749**	**105**	**42**	**0.38**
	st.dev	**168**	**58**	**33**	**0.13**
13.10.2004	107	427	244	84	0.34
		1111	70	50	0.71
		400	40	15	0.37
	average	**646**	**118**	**50**	**0.48**
	st.dev	**403**	**110**	**35**	**0.21**
2.11.2004	127	481	196	60	0.31
		612	173	57	0.33
		400	40	22	0.56
	average	**498**	**136**	**46**	**0.40**
	st.dev	**107**	**84**	**21**	**0.14**
13.11.2004	137	1429	57	13	0.22
		1714	57	15	0.26
		714	115	40	0.35
	average	**1286**	**76**	**23**	**0.28**
	st.dev	**515**	**33**	**15**	**0.07**

21.11.2004	146	741	120	40	0.33
		1667	50	18	0.37
		1111	50	12	0.25
	average	**1173**	**73**	**24**	**0.32**
	st.dev	**466**	**40**	**14**	**0.06**

Table 3.E Porosity of the biofilm created on the flat sheet membrane (experiment 1; Chapter 3)

Depth [um]/ Porosity [%]	20	60	160	240	280	340	360	380	400	580	620	640	660	720
#1	56.32	56.15	61.98	52.91	46.75	48.17	25.02	25.89	24.01	23.83	33.79	26.29	41.07	24.31
#2	63.41	67.71	59.11	53.02	54.65	40.62	23.64	28.42	24.03	32.49	25.90	38.13	35.69	31.96
#3	45.09	60.62	61.45	-	52.74	42.27	38.37	-	37.50	11.90	34.46	-	47.36	36.72
#4	60.62	62.74	55.53	-	36.46	-	-	-	-	26.54	33.34	-	38.45	39.17
#5	59.59	60.93	58.55	-	54.74	-	-	-	-	28.36	22.71	-	43.46	38.04
#6	-	-	-	-	50.76	-	-	-	-	-	-	-	41.42	42.75
#7	-	-	-	-	-	-	-	-	-	-	-	-	-	42.23
#8	-	-	-	-	-	-	-	-	-	-	-	-	-	35.83
#9	-	-	-	-	-	-	-	-	-	-	-	-	-	24.10
#10	-	-	-	-	-	-	-	-	-	-	-	-	-	39.11
#11	-	-	-	-	-	-	-	-	-	-	-	-	-	39.02
#12	-	-	-	-	-	-	-	-	-	-	-	-	-	35.63
#13	-	-	-	-	-	-	-	-	-	-	-	-	-	27.73
average	**57.00**	**61.63**	**59.33**	**52.96**	**49.35**	**43.69**	**29.01**	**27.15**	**28.52**	**24.62**	**30.04**	**32.21**	**41.24**	**35.12**
st.dev.	**6.37**	**3.73**	**2.31**	**0.08**	**6.98**	**3.97**	**8.14**	**1.79**	**7.78**	**7.78**	**5.37**	**8.37**	**4.03**	**6.27**

Table 4.A NO_3, NO_2 concentrations in influent and effluent from reactor #1 and #2 (experiment 2; Chapter 4)

		reactor #1						reactor #2					
		influent			effluent			Influent			effluent		
Date	day of the experiment	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
14.03.2005	1	14.55	14.55	0.00	14.55	14.55	0.00	14.55	14.55	0.00	14.55	14.55	0.00
15.03.2005	2	14.55	14.55	0.00	2.18	2.18	0.00	14.55	14.55	0.00	9.74	7.91	1.83
15.03.2005	2	-	-	-	0.00	0.00	0.00	-	-	-	9.43	4.43	5.00
15.03.2005	2	14.00	14.00	0.00	14.00	14.00	0.00	14.00	14.00	0.00	14.00	14.00	0.00
16.03.2005	3	-	-	-	0.93	0.56	0.36	-	-	-	13.60	7.15	6.45
16.03.2005	3	-	-	-	0.00	0.00	0.00	-	-	-	12.05	5.60	6.45
16.03.2005	3	13.07	13.07	0.00	12.07	12.07	0.00	13.07	13.07	0.00	13.15	13.15	0.00
17.03.2005	4	13.90	13.90	0.00	0.00	0.00	0.00	13.90	13.90	0.00	0.00	0.00	0.00
17.03.2005	4	-	-	-	13.90	13.90	0.00	-	-	-	13.90	13.90	0.00
18.03.2005	5	13.90	13.90	0.00	0.00	0.00	0.00	13.90	13.90	0.00	0.00	0.00	0.00
18.03.2005	5	14.94	14.94	0.00	0.00	0.00	0.00	14.94	14.94	0.00	0.00	0.00	0.00
19.03.2005	6	14.44	14.44	0.00	0.00	0.00	0.00	14.44	14.44	0.00	0.00	0.00	0.00
19.03.2005	6	-	-	-	5.43	3.96	1.47	-	-	-	3.95	2.95	1.00
20.03.2005	7	14.57	14.57	0.00	0.00	0.00	0.00	14.57	14.57	0.00	0.00	0.00	0.00
21.03.2005	8	-	-	-	0.00	0.00	0.00	-	-	-	0.00	0.00	0.00
22.03.2005	9	14.82	13.93	0.90	0.00	0.00	0.00	12.88	11.83	1.05	0.00	0.00	0.00
23.03.2005	10	14.61	14.61	0.00	2.06	1.08	0.97	12.33	12.11	0.22	1.51	0.92	0.60
24.03.2005	11	14.17	13.80	0.37	1.30	0.92	0.37	12.44	12.37	0.07	0.65	0.43	0.22
25.03.2005	12	13.74	12.99	0.75	1.24	1.02	0.22	12.44	12.29	0.15	0.00	0.00	0.00
26.03.2005	13	13.85	13.33	0.52	1.51	0.99	0.52	12.33	11.44	0.90	1.30	0.78	0.52
27.03.2005	14	13.42	13.42	0.00	2.71	1.51	1.20	11.58	11.43	0.15	1.41	1.18	0.22
28.03.2005	15	14.54	14.54	0.00	2.57	2.13	0.44	14.20	14.20	0.00	0.00	0.00	0.00
29.03.2005	16	14.65	14.65	0.00	2.25	1.52	0.72	14.36	14.36	0.00	0.00	0.00	0.00

30.03.2005	17	16.10	15.81	0.29	4.21	2.90	1.30	14.65	14.65	0.00	0.00	0.00	0.00
31.03.2005	18	14.57	14.57	0.00	1.46	1.13	0.33	14.45	14.45	0.00	0.00	0.00	0.00
01.04.2005	19	14.57	14.57	0.00	1.46	1.35	0.11	14.70	14.70	0.00	0.00	0.00	0.00
02.04.2005	20	14.33	14.33	0.00	0.97	0.86	0.11	14.70	14.70	0.00	0.00	0.00	0.00
03.04.2005	21	14.57	14.57	0.00	1.09	0.87	0.22	14.21	14.21	0.00	0.00	0.00	0.00
05.04.2005	23	16.20	16.20	0.00	0.30	0.30	0.00	17.83	17.83	0.00	0.00	0.00	0.00
06.04.2005	24	16.05	16.05	0.00	1.78	1.46	0.32	17.53	17.53	0.00	0.00	0.00	0.00
07.04.2005	25	16.94	16.94	0.00	5.35	2.56	2.79	17.83	17.83	0.00	1.04	0.72	0.32
08.04.2005	26	17.46	17.46	0.00	7.13	4.35	2.79	17.68	17.68	0.00	1.04	0.72	0.32
09.04.2005	27	17.24	17.24	0.00	3.72	2.76	0.96	17.39	17.39	0.00	2.67	1.72	0.96
10.04.2005	28	17.68	17.68	0.00	5.65	4.61	1.04	17.83	17.83	0.00	2.82	2.03	0.80
11.04.2005	29	14.05	14.05	0.00	5.46	4.62	0.83	14.41	14.41	0.00	2.15	2.15	0.00
12.04.2005	30	14.68	14.68	0.00	3.85	2.65	1.20	13.87	13.87	0.00	2.60	1.92	0.68
13.04.2005	31	15.55	15.55	0.00	3.33	2.58	0.74	15.23	15.23	0.00	0.00	0.00	0.00
14.04.2005	32	15.35	15.35	0.00	2.30	1.56	0.74	14.33	14.33	0.00	1.28	1.03	0.25
15.04.2005	33	15.35	15.35	0.00	4.22	3.36	0.87	14.07	14.07	0.00	0.77	0.58	0.19
16.04.2005	34	15.61	15.61	0.00	6.27	5.40	0.87	14.07	14.07	0.00	0.26	0.19	0.06
17.04.2005	35	15.74	15.74	0.00	6.14	5.40	0.74	13.82	13.82	0.00	0.00	0.00	0.00
18.04.2005	36	15.37	15.37	0.00	4.09	3.23	0.87	14.98	14.98	0.00	0.00	0.00	0.00
19.04.2005	37	46.28	45.46	0.81	4.15	0.57	3.58	61.05	61.05	0.00	0.00	0.00	0.00
20.04.2005	38	17.83	17.58	0.24	39.07	36.31	2.77	20.51	19.37	1.14	46.89	46.89	0.00
21.04.2005	39	15.38	15.30	0.08	4.15	2.85	1.30	17.22	17.22	0.00	5.62	0.00	5.62
22.04.2005	40	16.61	16.52	0.08	3.91	2.61	1.30	18.56	18.56	0.00	0.00	0.00	0.00
23.04.2005	41	15.38	14.57	0.81	4.27	3.22	1.06	17.58	17.58	0.00	3.42	2.93	0.49
24.04.2005	42	16.48	16.48	0.00	3.91	2.77	1.14	16.97	16.97	0.00	0.00	0.00	0.00
25.04.2005	43	16.19	11.40	4.79	4.88	3.58	1.30	15.33	15.33	0.00	0.00	0.00	0.00
26.04.2005	44	16.09	14.56	1.54	5.36	0.41	4.96	15.52	15.52	0.00	0.34	0.00	0.34
27.04.2005	45	16.19	15.85	0.34	4.69	2.30	2.39	15.71	15.71	0.00	0.34	0.00	0.34
28.04.2005	46	15.62	15.44	0.17	4.41	2.18	2.22	15.33	15.33	0.00	0.00	0.00	0.00

29.04.2005	47	15.81	15.64	0.17	5.17	3.12	2.05	15.33	15.33	0.00	0.00	0.00	0.00
30.04.2005	48	15.71	15.54	0.17	4.22	2.68	1.54	15.23	15.23	0.00	0.00	0.00	0.00
01.05.2005	49	15.62	15.44	0.17	4.79	2.82	1.97	15.25	15.25	0.00	0.00	0.00	0.00
02.05.2005	50	73.25	72.63	0.63	4.41	2.70	1.71	70.83	70.83	0.00	0.00	0.00	0.00
03.05.2005	51	76.89	76.26	0.63	69.32	67.51	1.81	78.40	77.77	0.63	53.28	51.84	1.44
04.05.2005	52	18.16	18.16	0.00	61.02	59.96	1.06	20.18	20.18	0.00	45.41	44.16	1.25
05.05.2005	53	18.36	18.36	0.00	11.60	8.85	2.75	19.78	19.78	0.00	3.03	2.15	0.88
06.05.2005	54	18.46	18.46	0.00	6.46	4.52	1.94	20.18	20.18	0.00	0.00	0.00	0.00
07.05.2005	55	18.36	18.36	0.00	6.26	3.69	2.56	19.57	19.57	0.00	0.00	0.00	0.00
08.05.2005	56	18.16	18.16	0.00	6.46	4.33	2.13	19.78	19.78	0.00	0.00	0.00	0.00
09.05.2005	57	16.12	13.88	2.24	6.26	4.88	1.38	15.84	15.84	0.00	1.21	0.84	0.38
10.05.2005	58	16.06	16.06	0.00	3.63	1.97	1.65	15.95	15.95	0.00	0.00	0.00	0.00
11.05.2005	59	16.01	16.01	0.00	5.69	4.39	1.30	15.78	15.78	0.00	0.00	0.00	0.00
12.05.2005	60	16.12	16.12	0.00	5.74	4.33	1.42	15.95	15.95	0.00	1.34	1.04	0.29
13.05.2005	61	15.55	15.55	0.00	5.47	4.05	1.42	16.67	16.67	0.00	0.00	0.00	0.00
14.05.2005	62	15.67	15.67	0.00	5.42	3.50	1.91	16.26	16.26	0.00	0.00	0.00	0.00
15.05.2005	63	15.67	15.67	0.00	6.95	5.29	1.66	15.90	15.90	0.00	0.00	0.00	0.00
16.05.2005	64	16.20	16.20	0.00	7.77	6.37	1.40	15.55	15.55	0.00	0.00	0.00	0.00
17.05.2005	65	14.68	9.57	5.11	4.50	3.61	0.89	16.01	10.91	5.11	0.00	0.00	0.00
18.05.2005	66	15.04	15.04	0.00	7.34	4.96	2.38	16.13	16.13	0.00	0.00	0.00	0.00
19.05.2005	67	14.68	14.68	0.00	6.39	4.76	1.63	16.13	16.13	0.00	0.00	0.00	0.00
20.05.2005	68	15.10	15.10	0.00	4.97	3.61	1.36	15.83	14.94	0.88	0.00	-0.75	0.75
21.05.2005	69	15.71	15.71	0.00	2.91	1.89	1.02	15.04	15.04	0.00	2.30	1.42	0.88
22.05.2005	70	15.47	15.47	0.00	4.37	2.39	1.97	16.01	16.01	0.00	0.00	0.00	0.00
23.05.2005	71	15.22	15.22	0.00	5.34	4.04	1.29	16.19	16.19	0.00	0.00	0.00	0.00
24.05.2005	72	14.48	14.48	0.00	3.09	1.94	1.16	15.52	15.52	0.00	1.58	0.96	0.61
25.05.2005	73	14.85	14.85	0.00	4.54	2.56	1.98	15.34	15.34	0.00	1.06	0.23	0.83
26.05.2005	74	14.85	14.85	0.00	2.37	1.10	1.28	15.59	15.59	0.00	0.00	0.00	0.00
27.05.2005	75	14.60	14.60	0.00	2.61	1.65	0.96	15.53	15.53	0.00	1.68	0.78	0.89

28.05.2005	76	14.54	14.54	0.00	1.68	0.91	0.77	15.34	15.34	0.00	0.38	0.00	0.38
29.05.2005	77	14.48	14.48	0.00	1.43	0.92	0.51	15.72	15.72	0.00	0.38	0.00	0.38
30.05.2005	78	15.59	15.59	0.00	1.55	-0.87	2.43	15.46	15.46	0.00	0.38	0.00	0.38
31.05.2005	79	15.12	14.62	0.50	2.82	2.52	0.30	16.13	16.13	0.00	0.65	0.00	0.65
01.06.2005	80	14.99	14.99	0.00	2.28	2.13	0.15	15.59	15.59	0.00	0.60	0.00	0.60
02.06.2005	81	14.92	14.92	0.00	2.28	2.18	0.10	15.86	15.86	0.00	0.00	0.00	0.00
03.06.2005	82	15.19	15.19	0.00	2.15	1.95	0.20	15.39	15.39	0.00	0.50	0.00	0.50
04.06.2005	83	14.92	14.92	0.00	1.75	0.44	1.31	15.46	15.46	0.00	2.15	0.24	1.91
05.06.2005	84	14.25	14.25	0.00	0.00	0.00	0.00	14.65	14.65	0.00	0.00	0.00	0.00
06.06.2005	85	14.90	14.90	0.00	0.46	0.46	0.00	16.04	15.94	0.10	0.57	0.47	0.10
07.06.2005	86	15.24	15.24	0.00	2.05	0.82	1.23	15.36	15.36	0.00	0.68	0.53	0.15
08.06.2005	87	15.13	15.13	0.00	0.91	0.81	0.10	15.70	15.70	0.00	0.34	0.24	0.10
09.06.2005	88	15.58	15.58	0.00	0.91	0.81	0.10	15.58	15.58	0.00	0.91	0.71	0.20
10.06.2005	89	14.90	14.90	0.00	1.14	1.06	0.08	15.27	15.22	0.05	0.34	0.34	0.00
11.06.2005	90	15.15	15.15	0.00	0.63	0.63	0.00	15.52	14.93	0.59	1.00	0.90	0.10
12.06.2005	91	14.90	14.90	0.00	0.88	0.78	0.10	15.34	15.34	0.00	1.63	1.33	0.30
13.06.2005	92	15.15	15.00	0.15	0.75	0.70	0.05	15.52	12.02	3.50	4.01	1.18	2.83
14.06.2005	93	14.52	14.52	0.00	0.75	0.70	0.05	15.65	15.65	0.00	0.88	0.68	0.20
15.06.2005	94	14.77	14.77	0.00	1.00	0.90	0.10	16.03	16.03	0.00	0.25	0.25	0.00
16.06.2005	95	15.15	15.15	0.00	1.13	0.93	0.20	15.78	15.78	0.00	1.75	1.31	0.45
17.06.2005	96	15.02	15.02	0.00	1.13	1.03	0.10	15.27	15.27	0.00	1.38	0.93	0.45
18.06.2005	97	15.90	15.90	0.00	1.25	0.95	0.30	15.90	15.90	0.00	2.13	1.24	0.89
19.06.2005	98	14.77	14.77	0.00	1.13	0.78	0.35	15.78	15.78	0.00	0.63	0.43	0.20
20.06.2005	99	14.18	10.52	3.66	1.25	0.71	0.55	14.60	10.53	4.07	1.00	0.75	0.25
21.06.2005	100	15.44	15.44	0.00	0.70	0.43	0.28	16.71	16.29	0.41	0.41	0.00	0.41
22.06.2005	101	26.25	24.87	1.38	1.26	0.57	0.69	16.78	16.23	0.55	1.68	0.86	0.83
23.06.2005	102	15.44	15.44	0.00	4.91	1.88	3.04	17.48	16.93	0.55	4.77	2.57	2.21
24.06.2005	103	15.02	15.02	0.00	1.54	0.85	0.69	17.76	17.35	0.41	6.11	3.62	2.48
25.06.2005	104	15.02	15.02	0.00	1.83	0.79	1.04	17.41	17.00	0.41	5.69	3.06	2.62

26.06.2005	105	15.30	15.30	0.00	2.04	0.52	1.52	18.04	17.42	0.62	6.25	2.80	3.45
27.06.2005	106	15.55	15.55	0.00	2.67	0.94	1.73	17.16	16.63	0.53	3.51	2.27	1.24
28.06.2005	107	15.55	15.55	0.00	3.22	1.22	2.00	16.76	16.44	0.32	3.35	1.98	1.37
29.06.2005	108	15.55	15.55	0.00	2.68	1.21	1.47	16.96	16.30	0.66	3.35	2.30	1.05
30.06.2005	109	14.60	14.01	0.59	2.28	1.12	1.16	16.36	16.04	0.32	3.89	2.52	1.37
01.07.2005	110	18.83	18.83	0.00	1.55	0.96	0.59	21.16	20.89	0.27	3.88	2.11	1.77
02.07.2005	111	18.76	18.71	0.05	5.50	2.93	2.58	21.58	21.26	0.32	7.62	5.92	1.70
03.07.2005	112	18.34	18.28	0.05	5.50	3.03	2.47	20.73	20.41	0.32	7.76	6.15	1.61
04.07.2005	113	19.89	13.43	6.46	6.21	3.42	2.79	21.51	20.87	0.64	8.18	6.89	1.29
05.07.2005	114	18.41	18.41	0.00	4.23	1.17	3.06	15.37	14.78	0.59	9.73	8.02	1.72
06.07.2005	115	18.25	16.23	2.02	6.98	3.39	3.59	15.81	15.28	0.52	5.92	4.21	1.72
07.07.2005	116	18.38	18.38	0.00	6.17	2.91	3.25	17.73	17.73	0.00	4.88	1.63	3.25
08.07.2005	117	18.76	18.76	0.00	7.90	3.22	4.69	19.02	19.02	0.00	6.36	4.02	2.34
09.07.2005	118	18.18	18.18	0.00	6.30	3.95	2.34	18.89	18.76	0.13	5.14	3.06	2.08
10.07.2005	119	18.89	18.89	0.00	7.58	4.72	2.86	18.12	18.12	0.00	5.01	3.45	1.56
11.07.2005	120	18.66	11.78	6.88	6.04	4.48	1.56	17.13	15.28	1.85	3.28	1.71	1.56
12.07.2005	121	18.66	18.66	0.00	5.95	3.76	2.20	19.67	19.67	0.00	3.41	1.54	1.87
13.07.2005	122	19.87	16.73	3.14	6.10	3.44	2.66	20.42	20.42	0.00	6.82	3.12	3.70
14.07.2005	123	19.95	19.95	0.00	5.81	4.28	1.54	21.68	20.84	0.84	7.93	3.47	4.47
15.07.2005	124	19.72	12.04	7.68	8.95	4.35	4.61	20.74	20.32	0.42	0.49	0.00	0.49
16.07.2005	125	26.00	26.00	0.00	12.73	5.61	7.12	21.92	21.22	0.70	6.91	4.40	2.51
17.07.2005	126	25.53	25.53	0.00	8.48	4.30	4.19	25.45	24.82	0.63	5.11	2.73	2.37
18.07.2005	127	24.05	19.93	4.13	7.07	3.16	3.91	23.59	19.70	3.89	7.48	4.55	2.93
19.07.2005	128	24.51	24.12	0.40	9.80	6.15	3.65	22.52	20.93	1.59	8.12	4.23	3.89
20.07.2005	129	24.44	24.20	0.24	6.43	4.61	1.83	22.06	20.79	1.27	4.75	3.16	1.59
21.07.2005	130	24.94	17.54	7.41	7.05	4.03	3.02	26.64	25.84	0.80	4.14	3.50	0.63
22.07.2005	131	25.00	25.00	0.00	9.82	3.89	5.93	25.31	24.92	0.40	10.77	2.46	8.32
23.07.2005	132	25.23	25.23	0.00	10.32	6.15	4.16	26.19	24.73	1.45	11.27	6.45	4.82
24.07.2005	133	24.44	24.44	0.00	9.52	4.63	4.89	26.66	25.21	1.45	10.24	5.53	4.70

25.07.2005	134	23.62	17.69	5.93	9.84	6.27	3.57	25.98	23.70	2.28	14.44	9.69	4.76
26.07.2005	135	25.76	24.62	1.14	10.04	1.95	8.09	28.15	26.09	2.05	13.28	6.56	6.72
27.07.2005	136	25.31	24.86	0.46	11.44	8.59	2.85	30.36	28.43	1.94	16.90	9.27	7.63
28.07.2005	137	24.95	24.95	0.00	11.81	8.16	3.65	28.01	25.88	2.13	16.31	10.61	5.70
29.07.2005	138	25.29	21.27	4.03	12.99	9.04	3.95	28.60	26.23	2.37	17.31	11.87	5.45
30.07.2005	139	24.61	24.61	0.00	15.70	9.70	6.00	29.45	27.00	2.45	19.35	13.19	6.16
31.07.2005	140	24.70	24.70	0.00	14.60	10.89	3.71	29.54	26.85	2.68	19.01	13.01	6.00
01.08.2005	141	24.95	24.95	0.00	13.58	8.29	5.29	27.92	25.16	2.76	13.58	6.24	7.34
02.08.2005	142	23.36	22.21	1.14	13.58	8.76	4.82	27.70	26.79	0.92	20.29	16.26	4.03
03.08.2005	143	24.90	24.90	0.00	16.02	11.14	4.88	29.34	27.51	1.83	19.31	15.03	4.27
04.08.2005	144	23.84	23.84	0.00	14.86	9.98	4.88	28.76	26.48	2.29	17.18	10.62	6.56
05.08.2005	145	24.45	17.87	6.58	6.18	4.65	1.53	30.50	29.66	0.84	16.22	10.39	5.83
06.08.2005	146	24.69	24.69	0.00	11.52	7.85	3.68	33.89	31.70	2.19	19.49	12.91	6.58
07.08.2005	147	25.42	25.42	0.00	11.62	9.60	2.03	34.38	32.18	2.19	20.22	20.22	0.00
08.08.2005	148	23.15	23.15	0.00	15.01	13.91	1.10	28.15	26.83	1.32	21.06	21.06	0.00
09.08.2005	149	22.84	21.01	1.83	13.66	12.24	1.42	28.99	25.33	3.66	10.95	7.70	3.25
10.08.2005	150	22.84	20.81	2.03	13.76	11.94	1.83	30.66	28.63	2.03	14.91	11.86	3.05
11.08.2005	151	0.00	0.00	0.00	10.22	8.19	2.03	0.00	0.00	0.00	18.77	15.22	3.55

Table 4.B Removal rates in reactor #1 and #2 – acclimation period (experiment 2; Chapter 4)

reactor #1			reactor #2		
Dairy removal	Daily removal	Removal rate	Dairy removal	Daily removal	Removal rate
mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}	mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}
14.27	256.78	0.66	17.83	320.98	0.78
11.59	208.63	0.53	16.49	296.90	0.72
10.33	185.90	0.48	16.79	302.25	0.74
13.52	243.41	0.62	15.01	270.15	0.66
12.04	216.66	0.56	14.56	262.13	0.64
8.59	154.66	0.40	15.68	282.31	0.69
10.83	194.93	0.50	11.81	212.65	0.52
12.22	219.95	0.56	13.87	249.71	0.61
13.05	234.92	0.60	13.95	251.04	0.61
11.13	200.37	0.51	13.56	244.13	0.60
9.34	168.13	0.43	13.82	248.73	0.61
9.60	172.73	0.44	14.07	253.34	0.62
11.28	202.96	0.52	13.82	248.73	0.61
42.12	758.24	1.94	14.98	269.64	0.66
-21.25	-382.42	-0.98	14.16	254.94	0.62
11.23	202.20	0.52	14.90	268.13	0.65
12.70	228.57	0.59	17.22	309.89	0.76
11.11	200.00	0.51	15.14	272.53	0.66
12.58	226.37	0.58	17.58	316.48	0.77
11.31	203.51	0.52	16.97	305.49	0.75
10.73	193.13	0.50	14.99	269.83	0.66
11.50	206.93	0.53	15.18	273.28	0.67
11.21	201.75	0.52	15.71	282.80	0.69
10.63	191.41	0.49	15.33	275.90	0.67
11.50	206.93	0.53	15.33	275.90	0.67
10.83	194.86	0.50	15.23	274.18	0.67
68.85	1239.24	3.18	15.25	274.52	0.67
7.57	136.22	0.35	17.56	316.02	0.77
-42.86	-771.52	-1.98	32.99	593.90	1.45
6.76	121.69	0.31	17.15	308.75	0.75
12.01	216.13	0.55	19.78	355.98	0.87
12.11	217.94	0.56	20.18	363.24	0.89
11.70	210.68	0.54	19.57	352.34	0.86
9.86	177.54	0.46	18.57	334.18	0.82
12.44	223.88	0.57	15.84	285.12	0.70
10.32	185.73	0.48	15.95	287.13	0.70
10.37	186.73	0.48	14.45	260.02	0.63
10.08	181.51	0.47	15.95	287.13	0.70
10.25	184.47	0.47	16.67	300.04	0.73

8.72	156.91	0.40	16.26	292.62	0.71
8.42	151.61	0.39	15.90	286.25	0.70
10.18	183.19	0.47	15.55	279.89	0.68
7.70	138.65	0.36	16.01	288.21	0.70
8.28	149.13	0.38	16.13	290.39	0.71
10.13	182.31	0.47	16.13	290.39	0.71
12.80	230.35	0.59	13.52	243.45	0.59
11.10	199.78	0.51	15.04	270.74	0.66
9.89	177.95	0.46	16.01	288.21	0.70
11.38	204.88	0.53	14.62	263.10	0.64
10.31	185.63	0.48	14.46	260.33	0.63
12.47	224.54	0.58	15.34	276.21	0.67
11.99	215.82	0.55	13.92	250.49	0.61
12.86	231.48	0.59	15.15	272.74	0.67
13.05	234.83	0.60	14.97	269.39	0.66
14.04	252.67	0.65	15.34	276.10	0.67
12.30	221.36	0.57	14.81	266.50	0.65
12.70	228.61	0.59	15.52	279.42	0.68
12.63	227.40	0.58	15.59	280.63	0.68
13.04	234.66	0.60	15.36	276.47	0.67
13.17	237.08	0.61	13.24	238.29	0.58
14.25	256.44	0.66	15.46	278.21	0.68
14.45	260.03	0.67	14.08	253.46	0.62
13.20	237.51	0.61	15.36	276.41	0.67
14.22	255.94	0.66	15.02	270.27	0.66
14.67	264.13	0.68	14.79	266.18	0.65
13.76	247.70	0.64	15.24	274.37	0.67
14.52	261.42	0.67	14.27	256.91	0.63
14.02	252.40	0.65	13.90	250.15	0.61
14.40	259.16	0.66	11.33	203.95	0.50
13.77	247.90	0.64	14.65	263.67	0.64
13.77	247.90	0.64	15.40	277.19	0.68
14.02	252.40	0.65	14.27	256.91	0.63
13.90	250.15	0.64	14.40	259.16	0.63
14.65	263.67	0.68	13.15	236.63	0.58
13.65	245.64	0.63	15.27	274.94	0.67
12.93	232.71	0.60	14.77	265.92	0.65
12.93	232.71	0.60	14.19	255.45	0.62

Table 4.C Removal rates in reactor #1 and #2 – influent concentration ~ 15 mg N l^{-1} (experiment 2; Chapter 4)

reactor #1			reactor #2		
Dairy removal	Daily removal	Removal rate	Dairy removal	Daily removal	Removal rate
mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}	mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}
14.18	204.20	0.52	15.02	270.41	0.66
21.34	307.31	0.79	12.00	216.08	0.53
13.90	200.15	0.51	11.37	204.70	0.50
13.20	190.05	0.49	12.07	217.34	0.53
12.99	187.01	0.48	11.16	200.91	0.49
12.64	181.96	0.47	14.53	261.57	0.64
12.33	177.59	0.46	13.81	248.53	0.61
12.87	185.31	0.48	13.41	241.29	0.59
13.27	191.10	0.49	13.07	235.26	0.57

Table 4.D Removal rates in reactor #1 and #2 – influent concentration ~ 20 mg N l^{-1} (experiment 2; Chapter 4)

reactor #1			reactor #2		
Dairy removal	Daily removal	Removal rate	Dairy removal	Daily removal	Removal rate
mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}	mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}
13.33	191.94	0.49	13.54	243.73	0.59
13.26	190.93	0.49	13.82	248.81	0.61
12.13	174.68	0.45	12.55	225.96	0.55
15.66	225.45	0.58	11.78	212.00	0.52
11.43	164.52	0.42	9.45	170.11	0.41
12.08	173.94	0.45	10.92	196.61	0.48
10.47	150.81	0.39	11.37	204.70	0.50
12.46	179.49	0.46	13.88	249.80	0.61
10.60	152.66	0.39	13.88	249.80	0.61
12.85	185.04	0.47	14.84	267.15	0.65
12.71	182.95	0.47	13.72	246.99	0.60
12.56	180.86	0.46	12.85	231.30	0.56
14.06	202.47	0.52	12.49	224.81	0.55
11.00	158.36	0.41	21.19	381.36	0.93
6.99	100.67	0.26	13.82	248.85	0.61

Table 4.E Removal rates in reactor #1 and #2 – influent concentration ~ 25 mg N l^{-1}, (experiment 2; Chapter 4)

reactor #1			reactor #2		
Dairy removal	Daily removal	Removal rate	Dairy removal	Daily removal	Removal rate
mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}	mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}
17.52	252.24	0.65	16.81	302.57	0.74
18.46	265.81	0.68	17.97	323.50	0.79
14.25	205.17	0.53	15.47	278.52	0.68
18.08	260.32	0.67	17.77	319.88	0.78
17.39	250.39	0.64	17.92	322.64	0.79
15.13	217.86	0.56	15.87	285.61	0.70
14.68	211.39	0.54	14.04	252.81	0.62
15.71	226.24	0.58	15.95	287.09	0.70
14.60	210.25	0.54	12.22	219.96	0.54
13.58	195.54	0.50	12.69	228.48	0.56
14.32	206.17	0.53	11.25	202.42	0.49
13.51	194.48	0.50	14.05	252.94	0.62
11.97	172.33	0.44	10.69	192.50	0.47
9.59	138.11	0.35	9.25	166.52	0.41
10.02	144.22	0.37	10.44	187.91	0.46
11.12	160.11	0.41	15.96	287.22	0.70
11.37	163.77	0.42	7.64	137.50	0.34

Table 4.F Removal rates in reactor #1 and #2 – influent concentration ~ 25 mg N l^{-1}+ pH control implementation (experiment 2; Chapter 4)

reactor #1			reactor #2		
buffer added			CO_2 added		
Dairy removal	Daily removal	Removal rate	Dairy removal	Daily removal	Removal rate
mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}	mg l^{-1}	mg d^{-1}	g N d^{-1} m^{-2}
7.34	105.64	0.27	12.16	218.92	0.53
10.04	144.56	0.37	12.55	323.50	0.79
17.66	254.36	0.65	11.02	198.28	0.48
12.93	186.17	0.48	13.68	246.22	0.60
13.07	188.26	0.48	13.32	239.68	0.58
10.41	149.91	0.38	17.21	309.70	0.76
9.49	136.64	0.35	14.08	253.39	0.62
9.07	130.64	0.33	11.89	213.97	0.52
12.62	181.69	0.47	-	-	-

Table 4.G pH, temperature and DO detected during the experiment #2 (experiment 2; Chapter 4)

		reactor #1			reactor #2		
Date	**Operational conditions & Loading**	**pH**	**temperature [°C]**	**DO [mg O_2 l^{-1}]**	**pH**	**temperature [°C]**	**DO [mg O_2 l^{-1}]**
14.03.2005	batch system, feed	7.70	19.0	7.0	7.70	18.0	6.1
15.03.2005		9.10	22.5	0.3	8.00	22.0	0.2
15.03.2005	batch system, waste	7.70	22.5	0.3	8.00	22.5	0.3
15.03.2005	batch system, feed	7.80	10.0	6.4	8.10	10.0	6.3
16.03.2005		7.90	23.0	0.2	7.90	23.0	0.2
16.03.2005	batch system, waste	7.20	23.0	0.2	7.30	23.0	0.2
16.03.2005	batch system, feed	0.20	22.0	7.0	0.20	22.0	6.4
17.03.2005		7.90	25.0	0.2	7.90	25.0	0.2
17.03.2005	batch system, waste	7.80	24.0	0.2	7.90	24.5	0.2
17.03.2005	batch system, feed	8.60	16.0	5.4	8.80	16.0	4.5
18.03.2005		8.00	25.0	0.2	8.00	24.0	0.2
18.03.2005	batch system, waste	7.60	25.0	0.2	7.60	24.0	0.2
18.03.2005	batch system, feed	9.00	22.0	4.6	9.20	22.0	3.4
19.03.2005	batch system, waste	9.00	24.0	0.2	9.20	23.0	0.2
19.03.2005	batch system, feed	7.90	22.0	4.7	7.90	22.0	4.4
20.03.2005	batch system, waste	7.70	24.0	0.3	7.70	24.0	0.3
20.03.2005	batch system, feed	9.00	22.0	1.6	9.00	22.0	1.6
21.03.2005		7.90	24.0	0.2	7.90	23.0	0.2
21.03.2005	batch system, waste	9.00	24.0	0.2	9.30	23.0	0.2
21.03.2005	batch system, feed	8.60	17.0	1.6	8.90	17.0	1.4
22.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.90	25.0	0.2	9.00	24.0	0.3
22.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.70	25.0	0.9	7.70	25.0	0.3
23.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	25.0	0.4	9.30	25.0	0.2
24.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.00	23.0	0.2	9.20	23.0	0.2
25.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.00	23.0	0.3	9.20	22.0	0.2

26.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	23.5	0.3	7.90	23.5	0.2
27.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	25.0	0.3	9.30	24.5	0.2
28.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.60	25.5	0.4	8.40	25.5	0.2
29.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	25.0	0.4	9.50	25.0	0.2
30.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	26.5	0.3	9.30	26.5	0.2
31.03.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	26.0	0.3	9.30	26.0	0.3
01.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.20	25.5	0.2	9.30	25.0	0.3
02.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.20	26.0	0.4	9.50	25.5	0.3
03.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	26.0	0.3	9.30	26.0	0.3
04.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.00	26.5	0.2	9.30	26.5	0.2
05.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.70	28.0	0.3	9.30	28.0	0.2
06.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.00	29.0	0.2	9.20	29.0	0.2
07.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.00	29.0	0.2	9.10	29.0	0.2
08.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	30.0	0.2	9.30	30.0	0.2
09.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.00	31.0	0.3	9.20	31.0	0.2
10.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.80	30.0	0.2	9.20	30.0	0.1
11.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.80	27.0	0.2	9.10	27.0	0.2
12.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.70	28.0	0.3	9.10	28.0	0.2
13.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.60	28.0	0.2	8.70	28.0	0.2
14.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	27.0	0.2	8.80	27.0	0.2
15.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	28.0	0.4	8.90	28.0	0.4
16.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.30	28.0	0.5	8.10	28.0	0.6
17.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	29.5	0.3	8.60	29.5	0.2
18.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	29.0	0.2	8.20	29.0	0.2
19.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.20	24.0	0.2	7.60	24.0	0.2
20.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	24.0	0.3	9.00	24.0	0.6
21.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	26.0	0.3	9.00	26.0	0.2
22.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.00	26.0	0.2	8.20	25.5	0.2
23.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.00	25.0	0.2	8.90	25.0	0.2

24.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	22.0	0.2	9.00	22.0	0.2
25.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	25.0	0.2	9.00	24.5	0.2
26.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	25.0	0.2	8.90	24.5	0.2
27.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.70	25.0	0.2	9.50	25.0	0.2
28.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.60	25.0	0.2	9.30	24.5	0.2
29.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	25.0	0.2	8.80	25.0	0.2
30.04.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	25.0	0.2	8.90	25.0	0.2
01.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	25.5	0.2	8.90	25.0	0.2
02.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	25.0	0.2	8.90	25.0	0.2
03.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	25.0	0.2	9.00	25.0	0.2
04.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	24.0	0.3	8.90	24.0	0.2
05.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	27.0	0.2	9.00	26.5	0.2
06.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	23.8	0.1	8.90	23.0	0.1
07.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	23.5	0.2	8.90	23.0	0.2
08.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.00	24.8	0.1	9.00	24.0	0.1
09.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	23.8	0.1	9.00	24.0	0.1
10.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.00	24.0	0.2	9.20	24.0	0.2
11.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.00	24.0	0.2	9.20	23.5	0.2
12.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	23.5	0.1	9.30	24.0	0.1
13.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	23.0	0.1	8.90	23.0	0.1
14.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	9.10	23.0	0.1	9.00	23.0	0.1
15.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	23.0	0.1	9.10	23.0	0.1
16.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	24.5	0.1	9.10	24.5	0.1
17.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	24.0	0.1	9.10	24.0	0.2
18.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.10	24.0	0.3	9.00	24.0	0.2
19.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.80	23.0	0.2	9.20	23.0	0.1
20.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.80	23.0	0.3	8.30	23.0	0.1
21.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.80	22.0	0.1	8.30	22.0	0.1
22.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	22.0	0.1	8.30	22.0	0.1

23.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.50	22.0	0.1	8.30	22.0	0.2
24.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.70	22.0	0.1	8.20	22.0	0.1
25.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	22.0	0.1	8.20	22.0	0.1
26.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	22.0	0.1	8.30	21.8	0.1
27.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	7.90	24.5	0.1	8.30	24.0	0.1
28.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.00	24.0	0.1	8.70	24.0	0.1
29.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	24.0	0.1	8.80	24.0	0.1
30.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.20	23.5	0.1	8.50	23.0	0.1
31.05.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.36	24.0	0.1	8.59	23.5	0.1
01.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	24.0	0.1	8.74	23.0	0.1
02.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	24.0	0.2	8.70	23.5	0.1
03.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	25.0	0.1	8.60	24.3	0.1
04.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	24.0	0.1	8.60	23.5	0.1
06.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	22.5	0.1	8.60	22.5	0.1
07.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.40	25.5	0.1	8.70	25.0	0.1
08.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.32	23.0	0.1	8.50	22.8	0.1
09.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.38	23.0	0.1	8.57	22.5	0.1
10.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.30	24.0	0.1	8.62	23.0	0.1
11.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.33	23.7	0.1	8.54	23.8	0.1
12.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.70	23.2	0.1	8.70	23.0	0.1
13.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.78	24.0	0.1	8.72	23.0	0.1
14.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.96	23.5	0.1	8.98	23.5	0.1
15.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.98	23.5	0.1	8.83	23.5	0.1
16.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.80	24.0	0.1	8.70	24.0	0.1
17.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.89	26.0	0.1	8.89	25.0	0.1
18.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.8 (9.06)	26.5	0.1	8.8 (9.05)	26.0	0.3
19.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.70	26.0	0.4	8.74	25.0	0.4
20.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.80	26.0	0.1	8.80	25.0	0.1
21.06.2005	continuous flow, 15 mg N l^{-1}, acclimation	8.80	26.0	0.1	8.80	25.0	0.1

22.06.2005	continuous flow, 15 mg N l^{-1}	8.70	26.0	0.1	8.90	25.0	0.1
23.06.2005	continuous flow, 15 mg N l^{-1}	8.70	25.5	0.1	8.80	24.5	0.1
24.06.2005	continuous flow, 15 mg N l^{-1}	8.70	26.0	0.1	8.90	25.8	0.1
25.06.2005	continuous flow, 15 mg N l^{-1}	8.60	26.2	0.0	8.80	26.2	0.1
26.06.2005	continuous flow, 15 mg N l^{-1}	8.60	26.6	0.1	8.80	26.4	0.1
27.06.2005	continuous flow, 15 mg N l^{-1}	8.50	26.2	0.1	8.80	26.2	0.2
28.06.2005	continuous flow, 15 mg N l^{-1}	8.50	26.4	0.1	8.70	26.3	0.3
29.06.2005	continuous flow, 15 mg N l^{-1}	8.60	26.3	0.1	8.20	26.4	0.3
30.06.2005	continuous flow, 15 mg N l^{-1}	8.50	25.9	0.2	8.00	25.5	0.1
01.07.2005	continuous flow, 15 mg N l^{-1}	8.60	26.7	0.1	8.20	26.4	0.3
02.07.2005	continuous flow, 20 mg N l^{-1}	8.60	27.3	0.2	8.50	27.0	0.4
03.07.2005	continuous flow, 20 mg N l^{-1}	8.40	26.8	0.2	8.40	26.5	0.3
04.07.2005	continuous flow, 20 mg N l^{-1}	8.50	26.7	0.3	8.40	26.2	0.2
05.07.2005	continuous flow, 20 mg N l^{-1}	8.60	24.8	0.1	8.40	24.0	0.2
06.07.2005	continuous flow, 20 mg N l^{-1}	8.60	25.5	0.1	8.45	25.0	0.1
07.07.2005	continuous flow, 20 mg N l^{-1}	8.60	26.0	0.2	8.17	25.7	0.3
08.07.2005	continuous flow, 20 mg N l^{-1}	8.80	26.3	0.1	8.40	25.8	0.1
09.07.2005	continuous flow, 20 mg N l^{-1}	8.50	27.1	0.1	8.40	27.0	0.1
10.07.2005	continuous flow, 20 mg N l^{-1}	8.50	28.0	0.2	8.20	28.0	0.1
11.07.2005	continuous flow, 20 mg N l^{-1}	8.60	27.0	0.1	8.20	26.5	0.1
12.07.2005	continuous flow, 20 mg N l^{-1}	8.70	28.5	0.1	8.20	28.0	0.1
13.07.2005	continuous flow, 20 mg N l^{-1}	8.50	28.0	0.1	8.50	28.0	0.1
14.07.2005	continuous flow, 20 mg N l^{-1}	8.40	27.0	0.1	8.60	27.0	0.1
15.07.2005	continuous flow, 20 mg N l^{-1}	8.40	27.5	0.0	8.50	28.0	0
16.07.2005	continuous flow, 20 mg N l^{-1}	8.50	27.3	0.2	8.60	27.3	0.2
17.07.2005	continuous flow, 25 mg N l^{-1}	8.50	25.5	0.1	8.60	25.5	0.3
18.07.2005	continuous flow, 25 mg N l^{-1}	8.40	25.0	-	8.70	25.0	-
19.07.2005	continuous flow, 25 mg N l^{-1}	8.30	25.5	-	8.90	25.5	-
20.07.2005	continuous flow, 25 mg N l^{-1}	8.44	24.8	0.2	7.89	25.0	0.2

21.07.2005	continuous flow, 25 mg N l^{-1}	8.45	25.0	0.4	8.93	25.0	0.1
22.07.2005	continuous flow, 25 mg N l^{-1}	8.60	25.5	0.2	8.80	25.5	0.2
23.07.2005	continuous flow, 25 mg N l^{-1}	8.60	26.0	0.2	8.70	26.0	0.2
24.07.2005	continuous flow, 25 mg N l^{-1}	8.70	25.5	0.2	9.00	25.5	0.3
25.07.2005	continuous flow, 25 mg N l^{-1}	8.90	25.5	0.2	8.90	25.5	0.2
26.07.2005	continuous flow, 25 mg N l^{-1}	8.90	25.3	0.3	8.90	25.3	0.4
27.07.2005	continuous flow, 25 mg N l^{-1}	9.00	24.5	0.4	8.90	24.5	0.4
28.07.2005	continuous flow, 25 mg N l^{-1}	8.90	24.0	0.2	8.90	24.0	0.1
29.07.2005	continuous flow, 25 mg N l^{-1}	8.90	27.0	0.2	8.50	26.5	0.2
01.08.2005	continuous flow, 25 mg N l^{-1}	8.80	27.0	0.6	8.40	27.0	0.1
02.08.2005	continuous flow, 25 mg N l^{-1}	8.70	27.5	0.2	8.50	27.6	0.2
03.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	8.85	26.5	0.2	8.75	26.0	0.1
04.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	9.05	25.5	0.3	8.74	25.5	0.6
05.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	8.93	26.0	0.5	8.57	25.5	0.3
06.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	8.80	25.9	0.1	8.80	25.7	1.1
07.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	9.22	26.0	0.4	8.76	25.0	0.4
08.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	8.70	26.0	0.1	8.80	26.0	0.4
09.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	8.50	25.5	0.4	8.60	26.0	0.7
10.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	8.83	26.0	0.7	7.42	26.0	0.6
11.08.2005	continuous flow, 25 mg N l^{-1}, buffer & CO_2	9.06	25.0	0.3	7.40	24.0	0.6

Table 4.H TSS and VSS concentrations in effluent (experiment 2; Chapter 4)

		reactor #1		reactor #2	
Date	day of the experiment	TSS	VSS	TSS	VSS
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
14.03.2005	1	15520.8	12291.7	15520.8	12291.7
15.03.2005	2	10.0	0.0	15.0	10.0
16.03.2005	3	0.0	0.0	0.0	0.0
17.03.2005	4	22.5	12.5	30.0	10.0
18.03.2005	5	5.0	5.0	3.3	3.3
19.03.2005	6	0.0	0.0	8.7	5.0
20.03.2005	7	7.5	2.5	3.8	1.3
21.03.2005	8	17.5	11.3	17.5	12.5
22.03.2005	9	17.5	5.0	10.0	2.5
23.03.2005	10	16.0	6.0	15.0	4.0
24.03.2005	11	-	-	-	-
25.03.2005	12	2.2	2.2	11.5	5.3
26.03.2005	13	7.4	7.4	6.4	3.8
27.03.2005	14	4.0	4.0	2.9	2.9
28.03.2005	15	7.0	7.0	2.0	2.0
29.03.2005	16	0.0	0.0	8.8	8.8
30.03.2005	17	-	-	-	-
31.03.2005	18	-	-	-	-
01.04.2005	19	5.0	0.0	11.0	9.0
02.04.2005	20	6.2	4.8	2.5	2.0
03.04.2005	21	7.0	2.0	0.5	0.5
05.04.2005	23	3.5	3.0	3.5	3.5
06.04.2005	24	0.0	0.0	4.6	0.5
07.04.2005	25	4.0	1.5	3.5	0.0
08.04.2005	26	4.5	1.0	5.0	5.0
09.04.2005	27	-	-	-	-
10.04.2005	28	4.3	1.1	0.0	0.5
11.04.2005	29	-	-	-	-
12.04.2005	30	1.0	1.0	14.2	4.0
13.04.2005	31	2.0	1.0	3.9	2.2
14.04.2005	32	3.9	1.7	7.9	3.8
15.04.2005	33	4.0	4.0	12.2	9.4
16.04.2005	34	2.8	1.7	8.3	8.3
17.04.2005	35	7.2	4.4	3.1	3.1
18.04.2005	36	4.4	3.9	3.9	3.3
19.04.2005	37	1.7	1.7	3.3	3.3
20.04.2005	38	4.9	3.8	0.5	0.5
21.04.2005	39	3.9	3.9	5.0	3.1
22.04.2005	40	1.7	1.2	3.6	3.0
23.04.2005	41	6.5	1.2	0.5	1.1

24.04.2005	42	-	-	-	-
25.04.2005	43	5.5	4.4	6.1	6.1
26.04.2005	44	2.3	0.6	4.4	4.1
27.04.2005	45	11.7	11.1	3.3	3.6
28.04.2005	46	6.7	6.4	3.9	3.6
29.04.2005	47	5.5	5.0	6.1	4.7
30.04.2005	48	-	-	-	-
01.05.2005	49	6.9	6.9	5.3	2.9
02.05.2005	50	6.4	5.8	4.2	3.1
03.05.2005	51	4.3	2.4	3.5	2.9
04.05.2005	52	4.5	3.7	2.9	2.9
05.05.2005	53	4.2	4.2	3.9	3.9
06.05.2005	54	2.5	2.2	6.1	6.1
07.05.2005	55	8.0	6.4	2.9	2.4
08.05.2005	56	-	-	-	-
09.05.2005	57	-	-	-	-
10.05.2005	58	4.4	4.4	12.0	12.0
11.05.2005	59	3.9	3.9	5.0	2.8
12.05.2005	60	8.9	6.1	20.5	11.9
13.05.2005	61	17.2	10.3	7.2	6.1
14.05.2005	62	-	-	-	-
15.05.2005	63	8.1	6.1	6.3	5.9
16.05.2005	64	8.2	8.2	6.1	4.7
17.05.2005	65	7.8	6.1	5.8	4.4
18.05.2005	66	8.3	6.9	6.1	6.1
19.05.2005	67	5.0	3.3	4.8	2.9
20.05.2005	68	6.4	4.2	3.6	3.6
21.05.2005	69	3.3	2.5	4.7	4.7
22.05.2005	70	7.8	7.2	4.3	2.9
23.05.2005	71	8.9	0.6	9.6	5.8
24.05.2005	72	9.4	6.6	5.8	4.2
25.05.2005	73	8.1	6.1	4.7	4.4
26.05.2005	74	4.7	4.7	5.6	4.7
27.05.2005	75	7.5	6.4	3.1	3.1
28.05.2005	76	3.3	6.4	2.2	1.4
29.05.2005	77	4.4	5.0	36.1	3.1
30.05.2005	78	14.2	5.3	3.3	2.5
31.05.2005	79	4.7	4.2	6.9	4.7
01.06.2005	80	7.8	6.1	4.4	3.3
02.06.2005	81	5.6	4.7	2.5	3.3
03.06.2005	82	5.6	5.3	4.2	4.2
04.06.2005	83	3.6	3.6	1.7	0.6
05.06.2005	84	-	-	-	-
06.06.2005	85	2.2	0.6	6.6	5.5

07.06.2005	86	5.7	5.2	8.4	6.4
08.06.2005	87	8.0	5.8	5.8	3.8
09.06.2005	88	7.9	6.4	5.0	4.4
10.06.2005	89	5.4	4.7	9.8	8.4
11.06.2005	90	5.6	4.5	17.2	14.5
12.06.2005	91	4.6	4.4	4.9	3.9
13.06.2005	92	6.7	5.7	7.6	7.0
14.06.2005	93	9.8	8.5	8.6	7.9
15.06.2005	94	49.2	11.4	7.6	6.2
16.06.2005	95	9.2	8.0	6.8	5.9
17.06.2005	96	9.0	7.5	9.3	7.7
18.06.2005	97	12.1	10.0	10.5	8.3
19.06.2005	98	7.3	5.1	8.4	7.5
20.06.2005	99	5.1	4.6	7.1	6.9
21.06.2005	100	7.9	7.2	7.6	7.0
22.06.2005	101	7.7	6.5	6.7	6.1
23.06.2005	102	9.9	9.3	5.1	4.4
24.06.2005	103	10.7	9.4	3.9	3.5
25.06.2005	104	8.5	7.5	7.0	6.5
26.06.2005	105	3.5	2.9	4.9	4.3
27.06.2005	106	72.0	51.5	6.1	5.4
28.06.2005	107	12.6	11.3	8.9	7.9
29.06.2005	108	11.5	9.1	8.1	6.5
30.06.2005	109	10.2	8.5	6.1	4.1
01.07.2005	110	-	-	-	-
02.07.2005	111	-	-	-	-
03.07.2005	112	9.3	7.6	3.5	2.3
04.07.2005	113	7.5	4.8	2.9	2.7
05.07.2005	114	14.7	10.6	3.0	2.5
06.07.2005	115	11.3	10.1	9.3	6.9
07.07.2005	116	7.4	5.9	7.6	6.3
08.07.2005	117	6.4	5.9	6.2	5.2
09.07.2005	118	4.2	4.2	5.3	4.4
10.07.2005	119	4.4	4.4	12.0	7.5
11.07.2005	120	-	-	-	-
12.07.2005	121	8.3	4.3	17.4	11.1
13.07.2005	122	5.3	3.7	8.0	5.7
14.07.2005	123	5.0	4.4	79.1	44.0
15.07.2005	124	99.2	57.9	10.5	8.5
16.07.2005	125	11.7	8.2	10.0	10.3
17.07.2005	126	6.8	6.2	8.2	6.4
18.07.2005	127	4.8	3.3	23.5	13.4
19.07.2005	128	31.9	19.3	5.8	4.6
20.07.2005	129	9.0	6.6	8.6	8.1

21.07.2005	130	2.9	2.8	6.5	5.3
22.07.2005	131	7.1	5.4	7.4	4.3
23.07.2005	132	6.8	4.3	6.3	4.9
24.07.2005	133	5.7	4.6	3.3	2.1
25.07.2005	134	4.7	3.5	5.0	3.7
26.07.2005	135	6.7	5.7	2.7	1.9
27.07.2005	136	5.0	4.2	5.7	5.5
28.07.2005	137	21.6	14.4	3.4	3.0
29.07.2005	138	9.6	6.8	3.4	4.5
30.07.2005	139	-	-	-	-
31.07.2005	140	-	-	-	-
01.08.2005	141	5.6	5.4	3.6	3.5
02.08.2005	142	2.5	2.5	7.9	6.4
03.08.2005	143	16.1	9.3	2.6	1.8
04.08.2005	144	6.3	4.2	8.7	6.6
05.08.2005	145	13.3	8.3	3.4	3.3
06.08.2005	146	6.1	4.9	3.7	3.9
07.08.2005	147	4.3	2.8	5.1	4.1
08.08.2005	148	5.0	2.7	12.1	0.4
09.08.2005	149	26.3	1.7	4.7	4.2
10.08.2005	150	20.5	9.4	17.0	16.8
11.08.2005	151	3.7	3.0	5.9	3.5

Table 4.I TCOD and SCOD in influent to reactor #1 and #2 (experiment 2; Chapter 4)

	influent	reactor #1		reactor #2	
Date	day of the experiment	TCOD	SCOD	TCOD	SCOD
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
14.03.2005	1	83.72	98.36	83.72	98.36
15.03.2005	2	89.92	89.92	89.92	89.92
16.03.2005	3	88.32	88.32	88.32	88.32
17.03.2005	4	94.10	94.10	94.10	94.10
18.03.2005	5	97.94	-	97.94	-
18.03.2005	5	110.81	105.39	110.81	105.39
19.03.2005	6	60.83	60.83	60.83	60.83
21.03.2005	8	55.61	42.37	55.61	42.37
22.03.2005	9	55.64	47.96	47.96	47.96
23.03.2005	10	40.41	47.96	33.12	47.96
24.03.2005	11	44.61	-	62.28	-
25.03.2005	12	60.24	-	103.48	-
26.03.2005	13	78.93	-	58.22	-
27.03.2005	14	97.41	-	68.15	-
28.03.2005	15	79.49	-	70.67	-
29.03.2005	16	80.13	-	126.84	-
30.03.2005	17	57.32	-	40.90	-
31.03.2005	18	94.90	-	65.85	-
01.04.2005	19	50.59	-	57.73	-
02.04.2005	20	94.14	-	82.61	-
03.04.2005	21	81.48	-	66.40	-
05.04.2005	23	89.76	-	62.00	-
06.04.2005	24	68.08	-	71.86	-
07.04.2005	25	122.17	-	127.66	-
08.04.2005	26	64.17	-	143.59	-
09.04.2005	27	32.80	-	26.38	-
10.04.2005	28	55.26	-	37.47	-
11.04.2005	29	109.66	-	84.63	-
12.04.2005	30	35.05	-	39.38	-
13.04.2005	31	86.55	-	93.29	-
14.04.2005	32	115.43	-	50.18	-
15.04.2005	33	44.67	-	48.52	-
16.04.2005	34	119.77	-	137.89	-
17.04.2005	35	136.86	-	181.38	-
18.04.2005	36	87.03	-	81.26	-
19.04.2005	37	58.49	-	38.58	-
20.04.2005	38	108.00	-	91.33	-
21.04.2005	39	144.32	-	73.32	-
22.04.2005	40	47.50	-	38.90	-
23.04.2005	41	37.93	-	44.18	-

24.04.2005	42	68.78	-	74.36	-
25.04.2005	43	101.95	-	108.73	-
26.04.2005	44	87.03	-	81.74	-
27.04.2005	45	113.90	-	70.83	-
28.04.2005	46	121.21	-	178.49	-
29.04.2005	47	149.61	-	152.50	-
30.04.2005	48	74.52	-	46.60	-
01.05.2005	49	141.91	-	150.57	-
02.05.2005	50	76.45	-	94.74	-
03.05.2005	51	68.31	-	86.95	-
04.05.2005	52	125.30	-	73.17	-
05.05.2005	53	54.65	-	87.27	-
06.05.2005	54	107.73	-	130.60	-
07.05.2005	55	144.02	-	139.50	-
08.05.2005	56	99.23	-	106.45	-
09.05.2005	57	93.29	-	127.71	-
10.05.2005	58	64.68	-	146.72	-
11.05.2005	59	109.49	-	35.53	-
12.05.2005	60	98.00	-	107.73	-
13.05.2005	61	-	-	-	-
14.05.2005	62	-	-	-	-
15.05.2005	63	85.41	-	130.52	-
16.05.2005	64	112.54	-	126.03	-
17.05.2005	65	79.00	-	54.67	-
18.05.2005	66	52.11	-	78.78	-
19.05.2005	67	139.00	-	85.67	-
20.05.2005	68	118.00	-	119.00	-
21.05.2005	69	-	-	-	-
22.05.2005	70	128.25	-	70.00	-
23.05.2005	71	98.83	-	95.67	-
24.05.2005	72	76.17	-	123.67	-
25.05.2005	73	62.67	-	61.80	-
26.05.2005	74	61.75	-	51.67	-
27.05.2005	75	88.17	-	59.17	-
28.05.2005	76	53.00	-	57.29	-
29.05.2005	77	42.14	-	58.29	-
30.05.2005	78	121.17	-	102.00	-
31.05.2005	79	58.67	-	63.33	-
01.06.2005	80	63.50	-	70.67	-
02.06.2005	81	75.17	-	82.80	-
03.06.2005	82	59.33	-	96.00	-
04.06.2005	83	-	-	-	-
05.06.2005	84	51.17	-	43.50	-
06.06.2005	85	44.00	-	62.67	-

07.06.2005	86	59.33	-	59.33	-
08.06.2005	87	84.17	-	85.67	-
09.06.2005	88	61.67	-	59.83	-
10.06.2005	89	106.33	-	64.71	-
11.06.2005	90	94.17	-	75.83	-
12.06.2005	91	56.83	-	61.00	-
13.06.2005	92	65.33	-	69.00	-
14.06.2005	93	94.50	-	78.17	-
15.06.2005	94	54.50	-	60.67	-
16.06.2005	95	85.17	62.33	77.67	61.83
17.06.2005	96	60.00	-	51.00	-
18.06.2005	97	96.67	-	81.17	-
19.06.2005	98	54.17	30.17	70.17	50.67
20.06.2005	99	29.67	31.00	46.17	21.00
21.06.2005	100	78.00	50.83	36.17	46.00
22.06.2005	101	107.33	78.33	21.67	29.33
23.06.2005	102	64.50	56.33	56.67	56.50
24.06.2005	103	41.83	-	17.00	-
25.06.2005	104	58.00	-	13.50	-
26.06.2005	105	52.83	46.00	58.50	39.50
27.06.2005	106	128.17	95.33	76.17	64.00
28.06.2005	107	127.83	88.00	92.00	105.00
29.06.2005	108	114.83	81.83	73.00	67.67
30.06.2005	109	33.67	-	14.00	-
01.07.2005	110	78.00	-	55.00	-
02.07.2005	111	133.17	-	90.00	-
03.07.2005	112	152.17	133.17	128.17	84.67
04.07.2005	113	154.00	110.50	92.17	103.33
05.07.2005	114	132.50	87.50	114.67	94.83
06.07.2005	115	-	75.33	-	54.67
07.07.2005	116	57.50	101.33	77.00	98.60
08.07.2005	117	75.50	-	61.50	-
09.07.2005	118	64.00	-	36.33	-
10.07.2005	119	65.67	37.67	87.20	55.67
11.07.2005	120	77.50	46.33	90.50	78.17
12.07.2005	121	61.50	29.50	35.00	20.67
13.07.2005	122	94.33	55.67	33.17	43.17
14.07.2005	123	92.17	62.00	60.00	57.40
15.07.2005	124	53.71	-	49.83	-
16.07.2005	125	131.50	-	67.50	-
17.07.2005	126	87.83	79.17	75.83	78.50
18.07.2005	127	102.00	70.33	82.67	69.00
19.07.2005	128	62.33	81.50	55.17	63.33
20.07.2005	129	180.00	84.50	92.00	87.67

21.07.2005	130	60.67	63.00	34.83	35.83
22.07.2005	131	67.17	-	85.17	-
23.07.2005	132	83.67	-	56.83	-
24.07.2005	133	58.00	-	36.50	-
25.07.2005	134	88.00	56.33	69.00	58.00
26.07.2005	135	70.50	88.17	60.50	59.00
27.07.2005	136	85.50	-	60.17	-
28.07.2005	137	79.67	61.50	73.17	56.67
29.07.2005	138	75.67	85.50	48.83	46.83
30.07.2005	139	83.50	-	66.50	-
31.07.2005	140	-	-	-	-
01.08.2005	141	65.33	63.50	42.17	37.67
02.08.2005	142	79.33	43.17	43.00	41.17
03.08.2005	143	96.33	103.33	73.00	70.67
04.08.2005	144	118.83	109.33	54.50	50.00
05.08.2005	145	91.75	-	44.17	-
06.08.2005	146	69.00	-	55.17	-
07.08.2005	147	77.50	46.67	57.50	69.50
08.08.2005	148	87.33	50.00	55.50	38.50
09.08.2005	149	39.83	35.17	38.00	36.67
10.08.2005	150	68.17	44.17	48.83	27.50
11.08.2005	151	55.86	46.57	64.67	31.43

Table 4.J TCOD and SCOD in effluent from reactor #1 and #2 (experiment 2; Chapter 4)

	effluent	reactor #1		reactor #2	
Date	day of the experiment	TCOD	SCOD	TCOD	SCOD
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
14.03.2005	1	-	-	-	-
15.03.2005	2	83.49	51.91	108.06	84.19
16.03.2005	3	38.62	26.37	20.06	17.10
17.03.2005	4	117.92	63.38	102.04	70.61
18.03.2005	5	44.74	-	71.75	-
18.03.2005	5	53.58	56.13	39.68	56.03
19.03.2005	6	81.31	48.28	67.54	86.95
21.03.2005	8	42.66	39.94	42.83	36.91
22.03.2005	9	42.65	39.93	41.07	36.91
23.03.2005	10	71.05	50.29	90.52	63.03
24.03.2005	11	31.86	38.90	93.13	46.21
25.03.2005	12	73.92	56.64	112.13	92.00
26.03.2005	13	66.26	26.24	30.42	34.36
27.03.2005	14	51.89	30.04	48.32	41.65
28.03.2005	15	74.61	59.75	40.58	33.20
29.03.2005	16	49.41	60.90	86.02	64.11
30.03.2005	17	56.16	61.20	46.28	41.89
31.03.2005	18	71.49	36.85	32.00	23.09
01.04.2005	19	54.98	58.27	33.44	31.87
02.04.2005	20	65.21	63.69	26.38	36.73
03.04.2005	21	48.76	62.83	63.52	61.66
05.04.2005	23	40.10	45.40	56.68	51.95
06.04.2005	24	59.12	54.40	53.28	36.75
07.04.2005	25	74.01	61.52	95.70	42.75
08.04.2005	26	62.73	49.87	88.01	54.30
09.04.2005	27	72.11	50.93	62.00	49.49
10.04.2005	28	7.61	16.27	42.27	12.42
11.04.2005	29	65.85	45.64	65.59	54.53
12.04.2005	30	33.29	55.85	45.15	32.16
13.04.2005	31	41.78	30.23	11.10	75.96
14.04.2005	32	70.43	70.18	58.15	42.27
15.04.2005	33	91.85	18.68	165.08	128.43
16.04.2005	34	99.55	128.43	144.31	69.71
17.04.2005	35	134.21	115.43	132.28	130.36
18.04.2005	36	41.78	132.28	130.36	29.02
19.04.2005	37	41.79	59.59	36.17	31.36
20.04.2005	38	39.31	26.83	42.09	88.96
21.04.2005	39	36.97	38.58	66.66	50.61
22.04.2005	40	63.93	62.96	44.67	26.86
23.04.2005	41	55.74	43.71	29.75	31.89

24.04.2005	42	49.49	36.01	28.31	17.72
25.04.2005	43	7.13	21.09	3.76	9.53
26.04.2005	44	58.63	32.64	67.31	80.45
27.04.2005	45	81.74	50.93	88.96	37.45
28.04.2005	46	11.38	0.00	81.54	38.90
29.04.2005	47	96.66	63.93	50.45	94.50
30.04.2005	48	34.08	129.16	71.63	43.23
01.05.2005	49	147.20	139.02	81.74	78.85
02.05.2005	50	209.14	62.60	75.96	99.06
03.05.2005	51	138.06	127.53	114.31	93.93
04.05.2005	52	98.10	60.08	125.54	93.29
05.05.2005	53	44.67	56.23	49.00	114.95
06.05.2005	54	86.07	63.61	83.66	30.87
07.05.2005	55	69.46	109.30	82.45	99.78
08.05.2005	56	94.74	71.15	119.28	22.37
09.05.2005	57	107.44	65.68	114.28	52.38
10.05.2005	58	62.30	36.17	192.44	116.00
11.05.2005	59	68.50	52.37	43.07	135.23
12.05.2005	60	80.13	66.17	168.70	34.57
13.05.2005	61	96.34	65.76	109.82	115.91
14.05.2005	62	-	-	-	-
15.05.2005	63	-	-	-	-
16.05.2005	64	98.67	72.00	100.67	98.00
17.05.2005	65	49.44	56.83	93.93	72.59
18.05.2005	66	39.00	24.50	46.22	19.00
19.05.2005	67	80.13	38.67	94.56	48.78
20.05.2005	68	57.33	49.67	68.67	49.00
21.05.2005	69	64.50	53.00	62.67	66.50
22.05.2005	70	68.00	77.20	59.40	40.60
23.05.2005	71	48.50	49.00	85.00	49.75
24.05.2005	72	65.50	73.83	116.17	61.33
25.05.2005	73	63.17	54.83	84.67	71.33
26.05.2005	74	43.67	20.80	67.86	47.33
27.05.2005	75	37.20	15.67	72.50	40.00
28.05.2005	76	58.86	26.63	73.25	20.86
29.05.2005	77	35.67	27.25	13.50	27.17
30.05.2005	78	43.33	13.50	11.38	20.55
31.05.2005	79	72.83	59.83	54.83	72.83
01.06.2005	80	66.33	63.17	85.50	59.00
02.06.2005	81	42.83	36.50	51.50	34.33
03.06.2005	82	57.00	43.86	51.89	28.00
04.06.2005	83	44.00	27.67	52.00	46.33
05.06.2005	84	-	-	-	-
06.06.2005	85	57.83	52.50	76.67	35.00

07.06.2005	86	47.83	25.67	55.00	23.83
08.06.2005	87	36.67	28.17	56.33	21.83
09.06.2005	88	76.17	53.50	75.67	52.50
10.06.2005	89	52.33	40.00	27.83	30.67
11.06.2005	90	48.71	36.20	38.83	33.50
12.06.2005	91	42.50	45.00	50.50	26.83
13.06.2005	92	50.83	33.00	32.67	22.17
14.06.2005	93	73.00	36.67	63.00	37.17
15.06.2005	94	62.00	70.50	98.17	85.00
16.06.2005	95	35.83	28.33	35.50	26.50
17.06.2005	96	48.83	31.83	61.67	57.67
18.06.2005	97	44.17	18.50	29.33	28.83
19.06.2005	98	26.33	24.50	42.00	20.17
20.06.2005	99	21.40	14.33	42.00	33.83
21.06.2005	100	38.50	28.33	23.67	23.33
22.06.2005	101	45.83	37.00	63.67	51.00
23.06.2005	102	36.83	31.00	36.00	34.33
24.06.2005	103	57.33	104.50	109.60	67.57
25.06.2005	104	15.60	9.00	51.57	12.63
26.06.2005	105	37.40	18.50	38.67	10.69
27.06.2005	106	60.83	40.83	79.67	62.50
28.06.2005	107	53.17	62.17	90.33	66.00
29.06.2005	108	89.83	65.00	105.67	46.17
30.06.2005	109	66.50	63.50	84.17	61.00
01.07.2005	110	43.00	12.67	36.67	23.67
02.07.2005	111	22.33	20.00	37.33	31.00
03.07.2005	112	21.17	77.00	85.67	93.17
04.07.2005	113	123.50	64.17	103.67	115.17
05.07.2005	114	96.33	146.00	85.33	101.67
06.07.2005	115	126.17	67.33	123.00	105.17
07.07.2005	116	52.83	52.50	48.50	40.33
08.07.2005	117	136.00	54.67	127.80	81.00
09.07.2005	118	21.33	9.67	39.67	29.67
10.07.2005	119	16.83	9.33	45.67	27.50
11.07.2005	120	24.17	13.50	32.50	18.00
12.07.2005	121	24.17	48.50	77.67	67.50
13.07.2005	122	37.67	31.50	39.83	28.00
14.07.2005	123	99.50	51.33	47.83	47.17
15.07.2005	124	59.00	34.67	60.33	64.17
16.07.2005	125	41.00	38.33	38.00	26.00
17.07.2005	126	95.50	74.17	108.50	57.00
18.07.2005	127	69.00	55.83	100.00	65.50
19.07.2005	128	83.33	54.17	74.50	65.67
20.07.2005	129	40.67	35.50	69.00	51.50

21.07.2005	130	86.17	61.83	170.33	81.00
22.07.2005	131	47.17	38.40	55.17	67.33
23.07.2005	132	101.17	83.33	95.00	74.67
24.07.2005	133	76.83	43.50	94.67	74.33
25.07.2005	134	30.83	25.17	67.33	49.33
26.07.2005	135	75.67	61.33	80.50	68.00
27.07.2005	136	53.50	36.67	67.00	40.50
28.07.2005	137	32.50	40.83	68.67	58.83
29.07.2005	138	49.67	16.83	102.67	51.83
30.07.2005	139	32.67	-	64.17	-
31.07.2005	140	33.67	-	56.67	-
01.08.2005	141	75.67	62.00	80.83	87.67
02.08.2005	142	40.50	20.50	49.00	45.17
03.08.2005	143	53.00	45.67	59.83	37.00
04.08.2005	144	73.67	72.17	112.83	81.33
05.08.2005	145	64.17	49.29	58.86	62.43
06.08.2005	146	63.17	13.25	48.50	51.57
07.08.2005	147	33.50	36.00	58.00	66.50
08.08.2005	148	34.83	37.00	73.83	60.83
09.08.2005	149	43.00	34.83	54.83	48.67
10.08.2005	150	33.33	22.20	54.17	57.33
11.08.2005	151	37.17	27.50	47.17	45.33

Table 4.K Thickness, density (TS and VS content) as well as VS/TS ratio of the biofilm in reactor #1 (experiment 2; Chapter 4)

Date	Day of the experiment	Average biofilm thickness [µm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS
3.06.2005	82	516	177	54	0.31
		535	200	61	0.30
	average	**548**	**188**	**57**	**0.30**
	st.dev.	**13**	**16**	**5**	**0.30**
9.06.2005	88	897	61	24	0.39
		856	51	18	0.36
	average	**877**	**56**	**21**	**0.37**
	st.dev	**29**	**7**	**4**	**0.02**
16.06.2005	95	671	47	18	0.38
		559	70	18	0.26
		461	57	16	0.28
		472	149	51	0.33
	average	**540**	**81**	**26**	**0.31**
	st.dev	**97**	**46**	**17**	**0.05**
20.06.2005	99	323	115	33	0.29
		398	146	39	0.27
	average	**361**	**130**	**36**	**0.28**
	st.dev	**53**	**22**	**4**	**0.01**
30.06.2005	109	620	74	28	0.37
		253	216	62	0.29
	average	**437**	**145**	**45**	**0.33**
	st.dev	**260**	**100**	**24**	**0.06**
14.07.2005	123	494	246	81	0.33
		346	178	47	0.26
	average	**420**	**212**	**64**	**0.30**
	st.dev	**105**	**48**	**24**	**0.05**
18.07.2005	127	-	490	67	0.14
		-	247	107	0.43
	average	-	**368**	**87**	**0.28**
	st.dev	-	**172**	**28**	**0.21**
21.07.2005	130	-	193	67	0.34
		-	180	71	0.40
	average	-	**187**	**69**	**0.37**
	st.dev	-	**9**	**3**	**0.04**
25.07.2005	134	-	317	97	0.31
		-	136	49	0.36
	average	-	**226**	**73**	**0.33**
	st.dev	-	**128**	**34**	**0.04**
27.07.2005	136	-	169	58	0.34
		-	148	57	0.39
	average	-	**158**	**58**	**0.37**
	st.dev	-	**15**	**0**	**0.03**

02.08.2005	142	239	373	96	0.26
		301	235	65	0.28
	average	**270**	**304**	**81**	**0.27**
	st.dev	**44**	**98**	**22**	**0.01**
08.08.2005	147	201	380	108	0.28
		132	330	129	0.39
		110	310	100	0.32
		27	547	153	0.30
	average	**117**	**392**	**122**	**0.32**
	st.dev	**71**	**108**	**24**	**0.05**
12.08.2005	151	231	340	75	0.22
		202	314	70	0.22
		94	226	55	0.25
		141	251	66	0.25
	average	**167**	**283**	**67**	**0.24**
	st.dev	**62**	**53**	**8**	**0.02**

Table 4.L Thickness, density (TS and VS content) as well as VS/TS ratio of the biofilm in reactor #2 (experiment 2; Chapter 4)

Date	Day of the experiment	Average biofilm thickness [µm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS
3.06.2005	82	511	111	28	0.26
		651	108	29	0.27
	average	**548**	**109**	**29**	**0.26**
	st.dev	**98**	**2**	**0**	**0.26**
9.06.2005	88	993	48	14	0.28
		1291	66	29	0.43
	average	**1142**	**57**	**21**	**0.36**
	st.dev	**211**	**13**	**11**	**0.11**
16.06.2005	95	1098	65	27	0.41
		421	55	15	0.27
		548	117	32	0.27
		172	224	60	0.27
	average	**560**	**115**	**33**	**0.31**
	st.dev	**392**	**78**	**19**	**0.07**
20.06.2005	99	214	65	17	0.26
		524	80	27	0.33
	average	**369**	**72**	**22**	**0.29**
	st.dev	**219**	**11**	**7**	**0.06**
30.06.2005	109	912	150	63	0.42
		128	71	43	0.60
	average	**520**	**111**	**53**	**0.51**
	st.dev	**555**	**56**	**14**	**0.13**
14.07.2005	123	192	266	140	0.53
		171	531	240	0.45
	average	**181**	**399**	**190**	**0.49**
	st.dev	**15**	**188**	**71**	**0.05**
18.07.2005	127	-	166	40	0.24
		-	240	90	0.38
	average	-	**203**	**65**	**0.31**
	st.dev	-	**52**	**35**	**0.09**
21.07.2005	130	-	123	70	0.57
		-	102	38	0.38
	average	-	**113**	**54**	**0.47**
	st.dev	-	**15**	**22**	**0.13**
25.07.2005	134	-	129	56	0.44
		-	122	40	0.33
	average	-	**126**	**48**	**0.38**
	st.dev	-	**5**	**12**	**0.08**
27.07.2005	136	-	178	82	0.46
		-	240	89	0.37
	average	-	**209**	**85**	**0.41**
	st.dev	-	**44**	**5**	**0.06**

02.08.2005	142	403	282	90	0.32
		167	345	97	0.28
	average	**285**	**313**	**93**	**0.30**
	st.dev	**167**	**44**	**5**	**0.03**
08.08.2005	147	143	371	187	0.50
		239	184	100	0.54
		386	157	69	0.44
		248	263	120	0.45
	average	**254**	**244**	**119**	**0.48**
	st.dev	**100**	**96**	**50**	**0.05**
12.08.2005	151	25	101	49	0.48
		200	140	61	0.44
		495	155	80	0.52
		76	442	140	0.37
	average	**199**	**209**	**82**	**0.45**
	st.dev	**211**	**157**	**41**	**0.06**

Table 5.A NO_3, NO_2 concentrations in influent and effluent from reactor #1 and #2 (experiment 3, Chapter 5)

			reactor #1						reactor #2					
			influent			effluent			influent			effluent		
date	day of the experiment	operational conditions	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2
			$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$
17.01.2007	1	low mixing level	30.47	30.47	0.00	13.16	10.75	2.41	36.02	36.02	0.00	13.51	10.06	3.44
18.01.2007	2	low mixing level	17.54	17.21	0.33	11.37	10.38	0.99	16.96	16.63	0.33	5.59	4.60	0.99
19.01.2007	3	low mixing level	18.50	16.72	1.79	12.14	10.84	1.30	19.08	18.59	0.49	7.32	6.67	0.65
20.01.2007	4	low mixing level	19.28	18.54	0.73	11.28	9.98	1.30	20.05	19.56	0.49	9.83	9.18	0.65
21.01.2007	5	low mixing level	18.12	17.47	0.65	13.69	12.71	0.98	18.89	18.40	0.49	6.07	5.58	0.49
22.01.2007	6	low mixing level	18.12	17.47	0.65	7.32	6.35	0.98	19.95	19.54	0.41	8.48	7.99	0.49
23.01.2007	7	low mixing level	16.06	16.06	0.00	8.94	8.20	0.74	16.39	16.39	0.00	7.28	6.39	0.89
23.01.2007	7	low mixing level	16.06	16.06	0.00	0.83	0.83	0.00	16.39	16.39	0.00	3.31	3.31	0.00
24.01.2007	8	low mixing level	16.22	15.77	0.45	9.84	9.03	0.81	15.31	14.71	0.60	4.01	2.66	1.35
24.01.2007	8	low mixing level	16.22	15.77	0.45	0.91	0.10	0.81	16.22	15.62	0.60	0.00	0.00	0.00
25.01.2007	9	low mixing level	16.70	15.49	1.21	7.11	6.26	0.85	16.79	16.00	0.79	5.48	4.15	1.33
26.01.2007	10	low mixing level	17.39	16.57	0.81	8.65	7.32	1.33	15.85	15.12	0.73	7.11	5.77	1.33
27.01.2007	11	low mixing level	16.16	12.68	3.48	5.70	4.03	1.67	15.78	15.09	0.70	5.32	4.28	1.04
27.01.2007	12	low mixing level	16.54	16.02	0.52	8.18	7.03	1.15	16.35	15.48	0.87	6.85	5.28	1.57
29.01.2007	13	low mixing level	16.73	16.39	0.35	9.70	8.48	1.22	17.72	17.34	0.38	9.89	8.71	1.18
30.01.2007	14	low mixing level	17.61	17.12	0.49	10.06	8.70	1.37	16.54	15.76	0.78	9.87	8.60	1.27
30.01.2007	14	low mixing level	17.61	17.12	0.49	1.94	1.45	0.49	16.54	15.76	0.78	3.10	3.06	0.04
31.01.2007	15	low mixing level	13.55	12.96	0.59	6.68	5.51	1.17	15.09	14.16	0.94	7.35	6.09	1.27
31.01.2007	15	low mixing level	13.55	12.96	0.59	0.58	0.09	0.49	15.09	14.16	0.94	1.16	0.77	0.39
01.02.2007	16	high level of mixing	17.27	16.27	1.01	4.66	2.98	1.68	17.47	15.60	1.87	6.89	5.58	1.31
02.02.2007	17	high level of mixing	17.66	16.54	1.12	6.02	4.15	1.87	15.92	14.24	1.68	7.08	5.41	1.68
03.02.2007	18	high level of mixing	15.87	7.45	8.42	3.72	0.52	3.19	14.80	13.35	1.45	3.87	1.55	2.32
04.02.2007	19	high level of mixing	15.83	13.22	2.61	4.64	1.10	3.54	15.09	14.11	0.99	5.03	3.29	1.74

05.02.2007	20	high level of mixing	19.47	18.93	0.54	5.38	3.68	1.71	15.21	14.32	0.90	4.82	3.74	1.08
06.02.2007	21	high level of mixing	19.00	18.29	0.72	5.62	4.45	1.17	17.32	16.69	0.63	6.32	5.60	0.72
07.02.2007	22	high level of mixing	18.02	17.57	0.45	6.32	5.15	1.17	18.37	17.92	0.45	6.79	5.89	0.90
08.02.2007	23	high level of mixing	14.31	13.85	0.46	4.25	3.07	1.19	14.11	13.75	0.36	5.80	5.44	0.36
09.02.2007	24	high level of mixing	11.41	10.68	0.73	0.91	0.00	0.91	18.17	17.63	0.55	6.19	5.82	0.36
10.02.2007	25	high level of mixing	17.37	16.86	0.51	4.33	3.34	0.99	15.97	15.78	0.20	5.82	4.84	0.99
11.02.2007	26	high level of mixing	18.04	17.64	0.39	11.15	10.52	0.63	17.94	17.54	0.39	5.99	5.24	0.75
12.02.2007	27	high level of mixing	18.64	18.24	0.39	4.66	3.48	1.18	18.47	17.88	0.59	5.99	5.20	0.79
13.02.2007	28	high level of mixing	17.97	17.87	0.10	4.66	3.57	1.08	18.64	17.95	0.69	5.32	4.44	0.89
14.02.2007	29	high level of mixing	17.57	17.37	0.20	5.82	4.44	1.38	17.97	17.77	0.20	5.99	4.61	1.38
15.02.2007	30	high level of mixing	21.05	16.16	4.90	7.75	3.30	4.45	18.18	17.12	1.07	3.35	1.71	1.64
16.02.2007	31	high level of mixing	18.02	14.99	3.03	1.89	0.28	1.60	17.60	15.64	1.96	2.30	1.59	0.71
17.02.2007	32	medium level of mixing	17.18	16.29	0.89	2.51	1.27	1.25	17.33	16.44	0.89	3.60	2.07	1.53
18.02.2007	33	medium level of mixing	16.55	15.66	0.89	4.61	2.12	2.49	17.81	16.83	0.98	4.57	2.79	1.78
19.02.2007	34	medium level of mixing	17.49	16.10	1.39	4.19	3.12	1.07	17.70	16.63	1.07	7.12	5.24	1.89
20.02.2007	35	medium level of mixing	18.54	17.65	0.89	6.62	5.02	1.60	18.44	17.72	0.71	7.12	5.16	1.96
21.02.2007	36	medium level of mixing	17.56	12.11	5.45	7.63	4.81	2.81	18.72	17.83	0.89	7.40	6.68	0.71
22.02.2007	37	medium level of mixing	18.40	16.57	1.83	7.40	5.29	2.11	17.79	16.90	0.89	4.39	2.40	1.99
23.02.2007	38	medium level of mixing	17.56	15.03	2.53	6.93	4.54	2.39	18.95	18.06	0.89	4.85	3.87	0.98
24.02.2007	39	medium level of mixing	18.77	16.09	2.67	6.93	3.92	3.01	17.33	15.91	1.42	6.01	4.58	1.42
25.02.2007	40	medium level of mixing	17.45	15.34	2.11	6.93	4.12	2.81	17.98	17.05	0.93	4.16	3.45	0.71
26.02.2007	41	medium level of mixing	17.41	11.85	5.56	2.84	0.38	2.46	16.88	16.88	0.00	4.35	3.72	0.64
27.02.2007	42	medium level of mixing	17.60	16.63	0.97	5.90	5.08	0.82	16.65	13.47	3.19	4.26	3.66	0.60
28.02.2007	43	medium level of mixing	13.82	13.54	0.27	2.12	1.66	0.46	13.72	12.90	0.82	2.08	1.44	0.64
01.03.2007	44	medium level of mixing	-	-	-	-	-	-	-	-	-	-	-	-
02.03.2007	45	medium level of mixing	-	-	-	-	-	-	-	-	-	-	-	-
03.03.2007	46	medium level of mixing	-	-	-	-	-	-	-	-	-	-	-	-
04.03.2007	47	medium level of mixing	15.78	12.57	3.21	4.31	2.79	1.52	17.15	16.31	0.84	6.96	6.11	0.84
05.03.2007	48	medium level of mixing	18.13	17.29	0.84	7.55	6.62	0.93	9.11	8.44	0.68	2.74	1.90	0.84

06.03.2007	49	medium level of mixing	22.25	21.20	1.05	6.86	5.68	1.18	18.72	18.04	0.68	6.96	5.27	1.69
07.03.2007	50	medium level of mixing	10.29	10.04	0.25	2.76	2.43	0.34	19.60	19.60	0.00	5.19	2.62	2.57
08.03.2007	51	medium level of mixing	16.56	16.39	0.17	6.37	6.03	0.34	17.54	17.11	0.43	11.47	10.61	0.86
09.03.2007	52	medium level of mixing	17.15	16.98	0.17	6.96	6.28	0.68	18.52	18.35	0.17	15.39	14.53	0.86
10.03.2007	53	medium level of mixing	16.76	16.25	0.51	7.35	6.34	1.01	18.91	18.71	0.21	5.78	4.55	1.24
11.03.2007	54	medium level of mixing	16.37	15.35	1.01	4.61	3.39	1.22	15.58	15.38	0.21	8.37	7.00	1.37
12.03.2007	55	medium level of mixing	17.87	17.17	0.70	6.75	6.02	0.73	18.11	17.75	0.36	12.97	12.12	0.85
13.03.2007	56	medium level of mixing	18.32	17.92	0.40	7.64	7.09	0.55	19.74	19.37	0.37	14.04	13.20	0.84
14.03.2007	57	medium level of mixing	18.35	17.81	0.54	10.31	9.62	0.69	17.13	16.77	0.36	2.42	1.65	0.77
15.03.2007	58	medium level of mixing	18.28	17.85	0.43	7.88	6.87	1.01	17.86	17.62	0.24	3.70	2.75	0.95
16.03.2007	59	medium level of mixing	19.50	16.67	2.83	11.59	9.12	2.47	16.23	16.07	0.16	11.59	8.61	2.98
17.03.2007	60	medium level of mixing	16.44	16.09	0.35	5.90	5.13	0.77	17.50	16.83	0.67	7.17	5.96	1.21
18.03.2007	61	medium level of mixing	17.29	16.88	0.41	6.32	5.25	1.07	17.33	16.88	0.45	7.91	7.22	0.69
19.03.2007	62	medium level of mixing	17.29	16.83	0.46	8.22	7.38	0.84	16.44	16.05	0.39	8.85	7.89	0.96
20.03.2007	63	medium level of mixing	16.65	16.65	0.00	7.59	6.48	1.11	16.86	16.86	0.00	8.22	7.33	0.89
21.03.2007	64	medium level of mixing	18.94	18.49	0.45	1.79	1.13	0.67	18.19	17.79	0.40	5.23	4.79	0.45
22.03.2007	65	medium level of mixing	18.44	18.00	0.45	8.22	7.51	0.71	16.57	16.08	0.49	5.23	4.08	1.16
22.03.2007	65	medium level of mixing	18.14	0.00	0.00	8.72	0.00	0.00	18.19	0.00	0.00	9.59	0.00	0.00
23.03.2007	66	medium level of mixing	18.45	0.00	0.00	8.41	0.00	0.00	17.85	0.00	0.00	8.19	0.00	0.00
24.03.2007	67	medium level of mixing	17.11	15.32	1.79	9.27	5.70	3.57	18.05	17.58	0.48	9.13	6.94	2.19
25.03.2007	68	medium level of mixing	18.05	16.27	1.79	8.73	7.06	1.67	18.92	17.77	1.14	8.59	6.81	1.79
26.03.2007	69	medium level of mixing	18.86	17.43	1.43	9.40	7.86	1.55	19.13	18.23	0.91	8.32	6.42	1.91
27.03.2007	70	medium level of mixing	21.08	20.16	0.92	15.60	14.49	1.11	17.98	16.97	1.02	7.99	6.79	1.20
28.03.2007	71	medium level of mixing	22.31	0.00	0.00	13.45	0.00	0.00	19.65	0.00	0.00	8.30	0.00	0.00
29.03.2007	72	medium level of mixing	21.41	0.00	0.00	12.62	0.00	0.00	19.92	0.00	0.00	9.96	0.00	0.00
30.03.2007	73	medium level of mixing	17.53	17.02	0.51	8.02	6.80	1.22	17.53	16.91	0.62	10.19	8.52	1.67
31.03.2007	74	medium level of mixing	18.61	17.59	1.03	8.75	7.02	1.73	18.22	17.37	0.85	10.65	9.04	1.61
01.04.2007	75	medium level of mixing	19.06	17.92	1.14	9.59	7.82	1.77	19.34	18.78	0.56	12.61	11.30	1.32
02.04.2007	76	medium level of mixing	18.78	18.22	0.56	9.25	7.35	1.90	17.94	17.79	0.15	7.90	6.59	1.32

03.04.2007	77	high level of mixing+ low N_2 sparging	15.77	15.48	0.29	6.66	4.33	2.32	15.19	14.90	0.29	6.13	3.81	2.32
04.04.2007	78	high level of mixing+ low N_2 sparging	20.09	19.45	0.64	6.91	3.83	3.09	19.66	19.02	0.64	7.78	5.01	2.77
05.04.2007	79	high level of mixing+ low N_2 sparging	27.36	26.70	0.66	10.03	5.81	4.22	22.50	22.21	0.28	9.12	5.46	3.66
06.04.2007	80	high level of mixing+ low N_2 sparging	24.02	22.95	1.06	12.16	6.66	5.50	22.19	21.80	0.39	11.25	6.78	4.47
07.04.2007	81	high level of mixing+ low N_2 sparging	24.02	22.69	1.33	12.77	8.86	3.90	21.22	20.37	0.85	12.89	10.37	2.52
08.04.2007	82	high level of mixing+ low N_2 sparging	22.19	21.48	0.71	9.12	6.64	2.48	21.04	20.68	0.35	12.16	8.97	3.19
09.04.2007	83	high level of mixing+ low N_2 sparging	17.21	16.85	0.35	7.60	5.29	2.31	20.67	20.18	0.50	11.00	7.54	3.46
10.04.2007	84	high level of mixing+ low N_2 sparging	23.41	20.39	3.02	7.30	4.72	2.57	22.80	18.90	3.90	6.08	2.97	3.11
11.04.2007	85	high level of mixing+ low N_2 sparging	20.06	19.57	0.50	6.99	4.69	2.31	20.67	20.10	0.57	9.12	4.86	4.26
12.04.2007	86	high level of mixing+ low N_2 sparging	18.98	18.61	0.36	5.74	2.31	3.43	18.53	17.80	0.72	3.87	1.81	2.06
13.04.2007	87	high level of mixing+ low N_2 sparging	15.94	13.73	2.22	5.56	2.19	3.37	16.44	15.64	0.80	5.19	2.53	2.66
14.04.2007	88	high level of mixing+ low N_2 sparging	17.23	16.26	0.97	6.37	3.17	3.20	18.28	17.16	1.12	6.79	4.46	2.33
15.04.2007	89	high level of mixing+ low N_2 sparging	18.07	16.58	1.49	9.29	4.97	4.32	18.28	16.97	1.30	4.35	2.68	1.68
16.04.2007	90	high level of mixing+ low N_2 sparging	17.30	16.37	0.93	6.79	2.69	4.10	17.93	17.03	0.89	3.31	2.23	1.08
17.04.2007	91	high level of mixing+ low N_2 sparging	17.03	15.55	1.49	7.50	3.22	4.27	17.03	15.70	1.34	2.63	2.26	0.37
18.04.2007	92	high level of mixing+ low N_2 sparging	17.06	16.33	0.73	6.35	0.64	5.70	16.88	15.05	1.82	0.55	0.00	0.55
19.04.2007	93	high level of mixing+ low N_2 sparging	17.12	15.62	1.50	4.45	0.81	3.64	16.05	15.07	0.98	3.06	1.52	1.54

20.04.2007	94	high level of mixing+ low N_2 sparging	16.95	12.84	4.11	3.79	0.15	3.64	16.21	13.39	2.82	3.82	1.86	1.97
21.04.2007	95	high level of mixing+ low N_2 sparging	15.45	14.60	0.86	2.63	-1.40	4.02	16.90	15.23	1.67	1.54	0.26	1.28
22.04.2007	96	high level of mixing+ low N_2 sparging	17.92	16.42	1.50	2.84	0.70	2.14	15.89	14.82	1.07	2.08	1.44	0.64
23.04.2007	97	high level of mixing+ low N_2 sparging	16.42	15.78	0.64	0.69	-1.27	1.97	16.08	15.23	0.86	0.54	-0.11	0.64
24.04.2007	98	high level of mixing+ low N_2 sparging	16.80	16.80	0.00	2.70	0.14	2.57	16.99	15.92	1.07	3.40	2.37	1.03
25.04.2007	99	high level of mixing+ low N_2 sparging	18.17	15.56	2.61	1.43	0.36	1.07	18.78	18.35	0.43	0.20	-0.87	1.07
25.04.2007	99	high level of mixing+ low N_2 sparging	18.17	6.38	11.79	1.43	-3.41	4.83	18.78	16.85	1.93	0.20	-4.63	4.83
26.04.2007	100	high level of mixing+ low N_2 sparging	17.16	-	-	-	-	-	16.57	-	-	-	-	-
27.04.2007	101	high level of mixing+ low N_2 sparging	16.90	15.95	0.95	2.98	-0.26	3.24	16.06	14.27	1.79	0.00	0.00	0.00
28.04.2007	102	high level of mixing+ low N_2 sparging	14.69	-	-	2.23	-	-	13.38	-	-	2.18	-	-
29.04.2007	103	high level of mixing+ low N_2 sparging	15.23	-	-	2.45	-	-	12.24	-	-	0.00	-	-
30.04.2007	104	high level of mixing+ low N_2 sparging	15.50	-	-	2.58	-	-	11.70	-	-	0.00	-	-
01.05.2007	105	high level of mixing+ low N_2 sparging	15.59	15.10	0.49	0.97	0.34	0.64	16.29	15.78	0.51	0.47	0.24	0.23
02.05.2007	106	high level of mixing+ low N_2 sparging	15.59	14.57	1.03	0.56	0.17	0.39	14.97	13.70	1.27	0.40	0.30	0.10
03.05.2007	107	high level of mixing+ low N_2 sparging	17.08	14.66	2.41	0.41	0.24	0.17	16.56	13.64	2.92	0.29	0.29	0.00
04.05.2007	108	high level of mixing+ low N_2 sparging	15.72	13.69	2.03	0.15	0.01	0.14	15.91	13.50	2.41	0.00	0.00	0.00
05.05.2007	109	high level of mixing+ low N_2 sparging	15.75	0.00	0.00	0.32	0.00	0.00	15.67	0.00	0.00	0.71	0.00	0.00

06.05.2007	110	high level of mixing+ low N_2 sparging	15.35	0.00	0.00	0.32	0.00	0.00	16.46	0.00	0.00	1.42	0.00	0.00
07.05.2007	111	high level of mixing+ low N_2 sparging	15.51	14.35	1.16	0.69	0.04	0.64	15.51	14.35	1.16	2.21	0.34	1.87
08.05.2007	112	high level of mixing+ low N_2 sparging	16.19	15.03	1.16	0.80	0.80	0.00	16.49	16.49	0.00	0.34	-0.50	0.84
09.05.2007	113	high level of mixing+ medium N_2 sparging	19.51	19.14	0.37	1.92	0.70	1.22	18.23	17.75	0.47	0.73	0.73	0.00
10.05.2007	114	high level of mixing+ medium N_2 sparging	20.14	19.55	0.59	3.84	0.31	3.53	19.98	19.98	0.00	0.26	0.26	0.00
11.05.2007	115	high level of mixing+ medium N_2 sparging	21.14	20.32	0.82	6.60	3.30	3.29	19.55	18.95	0.60	0.00	0.00	0.00
12.05.2007	116	high level of mixing+ medium N_2 sparging	27.37	26.49	0.87	8.02	4.35	3.67	27.75	26.35	1.40	0.99	0.81	0.17
13.05.2007	117	high level of mixing+ medium N_2 sparging	27.33	26.11	1.22	6.88	3.56	3.32	27.75	26.79	0.96	0.19	0.02	0.17
14.05.2007	118	high level of mixing+ medium N_2 sparging	26.42	25.95	0.46	6.84	3.71	3.13	26.23	25.71	0.52	0.19	0.07	0.12
15.05.2007	119	high level of mixing+ medium N_2 sparging	19.53	18.96	0.58	3.94	0.77	3.16	18.91	18.20	0.72	0.00	0.00	0.00
16.05.2007	120	high level of mixing+ medium N_2 sparging	22.70	21.84	0.87	3.17	0.97	2.20	23.28	22.26	1.01	0.00	0.00	0.00
17.05.2007	121	high level of mixing+ medium N_2 sparging	19.28	18.25	1.03	3.76	0.06	3.70	19.12	18.09	1.03	0.78	0.36	0.42
18.05.2007	122	high level of mixing+ medium N_2 sparging	21.52	19.85	1.68	1.14	-0.80	1.94	21.55	19.97	1.59	0.16	-0.12	0.28
19.05.2007	123	high level of mixing+ medium N_2 sparging	21.47	20.66	0.81	5.77	1.79	3.98	21.47	20.28	1.19	0.00	0.00	0.00
20.05.2007	124	high level of mixing+ medium N_2 sparging	21.99	21.14	0.85	5.84	2.35	3.48	20.29	19.53	0.76	0.31	0.18	0.13
21.05.2007	125	high level of mixing+ medium N_2 sparging	20.29	19.15	1.14	4.89	4.68	0.22	19.67	18.63	1.03	0.21	-0.01	0.22
22.05.2007	126	high level of mixing+ medium N_2 sparging	20.22	20.01	0.22	5.03	2.09	2.94	19.90	18.87	1.03	0.47	0.04	0.44

23.05.2007	127	high level of mixing+ medium N_2 sparging	23.24	22.03	1.21	6.48	2.16	4.32	22.31	20.34	1.97	1.99	0.78	1.21
24.05.2007	128	high level of mixing+ medium N_2 sparging	22.30	16.46	5.83	5.71	1.27	4.44	21.01	19.93	1.08	1.92	0.44	1.48
25.05.2007	129	high level of mixing+ medium N_2 sparging	24.33	23.06	1.27	7.03	2.29	4.74	23.44	22.24	1.20	1.62	-0.28	1.90
26.05.2007	130	high level of mixing+ medium N_2 sparging	25.05	24.73	0.32	9.71	5.50	4.21	23.79	23.55	0.24	0.87	0.55	0.32
27.05.2007	131	high level of mixing+ medium N_2 sparging	25.15	23.37	1.78	8.74	4.52	4.21	23.98	23.17	0.81	2.82	0.87	1.95
28.05.2007	132	high level of mixing+ medium N_2 sparging	23.79	22.74	1.05	8.64	2.64	6.00	23.52	23.19	0.32	6.31	2.26	4.05
29.05.2007	133	high level of mixing+ medium N_2 sparging	21.99	18.67	3.32	7.65	3.23	4.43	22.17	19.75	2.42	5.45	0.94	4.51
30.05.2007	134	high level of mixing+ medium N_2 sparging	25.39	23.49	1.89	10.40	5.82	4.58	23.51	22.94	0.57	5.48	0.60	4.88
31.05.2007	135	high level of mixing+ medium N_2 sparging	6.72	5.82	0.90	0.00	-0.18	0.18	5.64	5.34	0.30	0.00	-0.15	0.15
01.06.2007	136	high level of mixing+ medium N_2 sparging	23.68	22.21	1.47	4.26	1.59	2.67	22.85	22.18	0.67	1.37	0.54	0.83
02.06.2007	137	high level of mixing+ medium N_2 sparging	21.94	21.04	0.90	4.54	3.64	0.90	19.31	19.31	0.00	0.16	0.16	0.00
03.06.2007	138	high level of mixing+ medium N_2 sparging	21.90	20.52	1.38	4.54	2.74	1.80	25.31	24.80	0.51	1.30	0.40	0.90
04.06.2007	139	high level of mixing+ medium N_2 sparging	22.59	21.83	0.75	5.19	3.57	1.62	22.39	21.91	0.48	3.25	1.29	1.95
05.06.2007	140	high level of mixing+ medium N_2 sparging	22.67	20.68	1.99	5.01	2.21	2.80	21.26	20.28	0.98	2.52	0.12	2.41
06.06.2007	141	high level of mixing+ medium N_2 sparging	24.30	23.39	0.90	5.62	3.39	2.23	22.22	21.46	0.75	2.37	0.14	2.23
07.06.2007	142	high level of mixing+ medium N_2 sparging	22.32	21.91	0.41	4.37	2.40	1.97	21.04	20.90	0.14	2.77	0.71	2.06
08.06.2007	143	high level of mixing+ high N_2 sparging	21.55	20.86	0.69	8.33	5.04	3.29	20.82	20.27	0.55	1.04	0.49	0.55

09.06.2007	144	high level of mixing+ high N_2 sparging	21.17	20.51	0.66	0.38	0.06	0.33	20.96	19.34	1.61	0.26	0.26	0.00
10.06.2007	145	high level of mixing+ high N_2 sparging	24.59	23.74	0.86	2.78	1.30	1.48	22.99	21.97	1.02	1.50	0.51	0.99
11.06.2007	146	high level of mixing+ high N_2 sparging	23.10	22.44	0.66	2.57	0.92	1.65	24.98	24.48	0.49	1.92	1.92	0.00
12.06.2007	147	high level of mixing+ high N_2 sparging	21.51	20.55	0.96	3.38	1.47	1.91	21.63	19.91	1.72	0.97	0.38	0.59
13.06.2007	148	high level of mixing+ high N_2 sparging	23.14	22.34	0.81	3.77	1.70	2.07	22.51	21.17	1.34	1.97	1.85	0.12
14.06.2007	149	high level of mixing+ high N_2 sparging	25.05	23.22	1.84	2.46	0.96	1.50	24.16	22.29	1.87	2.62	0.30	2.32
15.06.2007	150	high level of mixing+ high N_2 sparging	23.80	20.91	2.89	2.62	1.31	1.31	24.61	21.85	2.76	2.36	-1.05	2.36
16.06.2007	151	high level of mixing+ high N_2 sparging	26.23	22.93	3.30	0.59	0.59	0.00	26.91	24.42	2.49	5.69	1.03	4.66
17.06.2007	152	high level of mixing+ high N_2 sparging	28.08	25.02	3.06	0.74	0.71	0.03	28.67	26.82	1.85	7.70	1.88	5.82
18.06.2007	153	high level of mixing+ high N_2 sparging	28.08	26.76	1.32	6.44	3.78	2.65	28.08	27.60	0.48	9.79	3.20	6.59
19.06.2007	154	high level of mixing+ high N_2 sparging	28.88	26.58	2.30	5.82	3.25	2.57	27.26	25.10	2.16	9.00	4.31	4.68
20.06.2007	155	high level of mixing+ high N_2 sparging	26.70	24.10	2.60	4.31	1.96	2.35	25.50	23.44	2.06	6.77	1.68	5.09
21.06.2007	156	high level of mixing+ high N_2 sparging	25.90	23.46	2.44	3.31	0.69	2.62	25.20	23.00	2.20	6.08	0.87	5.21
22.06.2007	157	high level of mixing+ high N_2 sparging	25.30	23.58	1.72	2.27	0.74	1.53	25.20	23.32	1.88	5.32	1.36	3.96
23.06.2007	158	high level of mixing+ high N_2 sparging	26.20	24.19	2.01	6.78	4.02	2.76	26.20	24.31	1.89	7.58	2.64	4.94
24.06.2007	159	high level of mixing+ high N_2 sparging	28.20	26.52	1.68	6.40	3.41	2.99	28.10	26.28	1.82	5.85	2.00	3.85
25.06.2007	160	high level of mixing+ high N_2 sparging	27.90	25.89	2.01	7.26	4.08	3.18	28.50	27.63	0.87	8.37	2.90	5.47

26.06.2007	161	high level of mixing+ high N_2 sparging	26.30	22.89	3.41	0.43	0.26	0.16	27.40	24.90	2.50	5.24	1.24	4.00
27.06.2007	162	high level of mixing+ high N_2 sparging	26.50	23.94	2.56	5.26	2.63	2.63	28.90	26.77	2.13	10.60	4.20	6.40
28.06.2007	163	high level of mixing+ high N_2 sparging	31.30	29.63	1.67	11.20	4.29	6.91	29.20	27.24	1.96	14.90	3.50	11.40
29.06.2007	164	high level of mixing+ high N_2 sparging	29.10	28.05	1.05	9.55	5.60	3.95	24.90	23.99	0.91	11.60	4.38	7.22
30.06.2007	165	high level of mixing+ high N_2 sparging	28.00	26.91	1.09	9.50	5.65	3.85	28.20	27.08	1.12	11.20	3.93	7.27
01.07.2007	166	high level of mixing+ high N_2 sparging	27.70	26.37	1.33	8.98	4.90	4.08	28.70	27.46	1.24	12.30	3.48	8.82
02.07.2007	167	high level of mixing+ high N_2 sparging	28.80	27.64	1.16	9.72	6.06	3.66	28.40	27.40	1.00	13.50	6.07	7.43
03.07.2007	168	high level of mixing+ high N_2 sparging	28.30	27.01	1.29	14.60	11.27	3.33	30.00	28.94	1.06	6.81	3.09	3.72
04.07.2007	169	high level of mixing+ high N_2 sparging	30.50	29.30	1.20	8.83	5.34	3.49	30.70	29.60	1.10	6.53	2.76	3.77
05.07.2007	170	high level of mixing+ high N_2 sparging	28.90	27.69	1.21	7.72	4.74	2.98	30.10	29.18	0.92	8.58	5.68	2.90

Table 5.B Removal rates in reactor #1 and #2 (experiment 3, Chapter 5)

Date	day of the experiment	operational conditions	reactor #1	reactor #2
			[g N d^{-1} m^{-2}]	[g N d^{-1} m^{-2}]
17.01.2007	1	low mixing level	0.46	1.02
18.01.2007	1	low mixing level	0.32	0.57
19.01.2007	2	low mixing level	0.34	0.61
20.01.2007	3	low mixing level	0.43	0.53
21.01.2007	4	low mixing level	0.23	0.66
22.01.2007	5	low mixing level	0.56	0.57
23.01.2007	6	low mixing level	0.37	0.46
23.01.2007	7	low mixing level	0.79	0.65
24.01.2007	7	low mixing level	0.32	0.58
24.01.2007	8	low mixing level	0.77	0.83
25.01.2007	8	low mixing level	0.48	0.56
26.01.2007	9	low mixing level	0.45	0.43
27.01.2007	10	low mixing level	0.49	0.49
27.01.2007	11	low mixing level	0.45	0.49
29.01.2007	12	low mixing level	0.37	0.39
30.01.2007	13	low mixing level	0.40	0.35
30.01.2007	14	low mixing level	0.83	0.70
31.01.2007	14	low mixing level	0.35	0.39
31.01.2007	15	low mixing level	0.67	0.70
01.02.2007	15	high level of mixing	0.62	0.51
02.02.2007	16	high level of mixing	0.59	0.44
03.02.2007	17	high level of mixing	0.65	0.57
04.02.2007	18	high level of mixing	0.58	0.52
05.02.2007	19	high level of mixing	0.74	0.56
06.02.2007	20	high level of mixing	0.74	0.57
07.02.2007	21	high level of mixing	0.62	0.60
08.02.2007	22	high level of mixing	0.54	0.43
09.02.2007	23	high level of mixing	0.54	0.59
10.02.2007	24	high level of mixing	0.65	0.50
11.02.2007	25	high level of mixing	0.35	0.58
12.02.2007	26	high level of mixing	0.72	0.61
13.02.2007	27	high level of mixing	0.65	0.64
14.02.2007	28	high level of mixing	0.61	0.60
15.02.2007	29	high level of mixing	0.70	0.76
16.02.2007	30	high level of mixing	0.83	0.77
17.02.2007	31	medium level of mixing	0.74	0.66
18.02.2007	32	medium level of mixing	0.59	0.66
19.02.2007	33	medium level of mixing	0.67	0.51
20.02.2007	34	medium level of mixing	0.60	0.55
21.02.2007	35	medium level of mixing	0.93	1.03
22.02.2007	36	medium level of mixing	1.03	1.22

23.02.2007	37	medium level of mixing	0.52	0.69
24.02.2007	38	medium level of mixing	0.58	0.54
25.02.2007	39	medium level of mixing	0.50	0.65
26.02.2007	40	medium level of mixing	0.71	0.61
27.02.2007	41	medium level of mixing	0.56	0.58
28.02.2007	42	medium level of mixing	0.58	0.55
01.03.2007	43	medium level of mixing	0.00	0.00
02.03.2007	44	medium level of mixing	0.00	0.00
03.03.2007	45	medium level of mixing	0.00	0.00
04.03.2007	46	medium level of mixing	0.55	0.49
05.03.2007	47	medium level of mixing	0.54	0.32
06.03.2007	48	medium level of mixing	0.77	0.58
07.03.2007	49	medium level of mixing	0.37	0.71
08.03.2007	50	medium level of mixing	0.50	0.29
09.03.2007	51	medium level of mixing	0.47	0.15
10.03.2007	52	medium level of mixing	0.47	0.64
11.03.2007	53	medium level of mixing	0.56	0.34
12.03.2007	54	medium level of mixing	0.53	0.24
13.03.2007	55	medium level of mixing	0.51	0.27
14.03.2007	56	medium level of mixing	0.40	0.71
15.03.2007	57	medium level of mixing	0.53	0.70
16.03.2007	58	medium level of mixing	0.38	0.22
17.03.2007	59	medium level of mixing	0.51	0.50
18.03.2007	60	medium level of mixing	0.53	0.45
19.03.2007	61	medium level of mixing	0.46	0.37
20.03.2007	62	medium level of mixing	0.43	0.40
21.03.2007	63	medium level of mixing	0.85	0.62
22.03.2007	64	medium level of mixing	0.51	0.55
22.03.2007	64	medium level of mixing	0.47	0.42
23.03.2007	0	medium level of mixing	0.48	0.45
24.03.2007	66	medium level of mixing	0.37	0.41
25.03.2007	67	medium level of mixing	0.43	0.47
26.03.2007	68	medium level of mixing	0.44	0.50
27.03.2007	69	medium level of mixing	0.26	0.46
28.03.2007	70	medium level of mixing	0.42	0.55
29.03.2007	71	medium level of mixing	0.42	0.47
30.03.2007	72	medium level of mixing	0.46	0.35
31.03.2007	73	medium level of mixing	0.47	0.35
01.04.2007	74	medium level of mixing	0.45	0.32
02.04.2007	75	medium level of mixing	0.48	0.49
03.04.2007	76	high level of mixing+ low N_2 sparging	0.44	0.43
04.04.2007	77	high level of mixing+ low N_2 sparging	0.67	0.56
05.04.2007	78	high level of mixing+ low N_2 sparging	0.86	0.66

06.04.2007	79	high level of mixing+ low N_2 sparging	0.57	0.52
07.04.2007	80	high level of mixing+ low N_2 sparging	0.53	0.39
08.04.2007	81	high level of mixing+ low N_2 sparging	0.62	0.81
09.04.2007	82	high level of mixing+ low N_2 sparging	0.46	0.46
10.04.2007	83	high level of mixing+ low N_2 sparging	0.78	0.78
11.04.2007	84	high level of mixing+ low N_2 sparging	0.61	0.52
12.04.2007	85	high level of mixing+ low N_2 sparging	0.61	0.66
13.04.2007	86	high level of mixing+ low N_2 sparging	0.49	0.51
14.04.2007	87	high level of mixing+ low N_2 sparging	0.49	0.51
15.04.2007	88	high level of mixing+ low N_2 sparging	0.40	0.61
16.04.2007	89	high level of mixing+ low N_2 sparging	0.51	0.67
17.04.2007	90	high level of mixing+ low N_2 sparging	0.44	0.64
18.04.2007	91	high level of mixing+ low N_2 sparging	0.51	0.74
19.04.2007	92	high level of mixing+ low N_2 sparging	0.59	0.57
20.04.2007	93	high level of mixing+ low N_2 sparging	0.58	0.54
21.04.2007	94	high level of mixing+ low N_2 sparging	0.56	0.64
22.04.2007	95	high level of mixing+ low N_2 sparging	0.67	0.60
23.04.2007	96	high level of mixing+ low N_2 sparging	0.71	0.68
24.04.2007	97	high level of mixing+ low N_2 sparging	0.70	0.63
25.04.2007	98	high level of mixing+ low N_2 sparging	0.75	0.80
25.04.2007	98	high level of mixing+ low N_2 sparging	0.00	0.00
26.04.2007	99	high level of mixing+ low N_2 sparging	0.76	0.72
27.04.2007	100	high level of mixing+ low N_2 sparging	0.64	0.70
28.04.2007	101	high level of mixing+ low N_2 sparging	0.57	0.48
29.04.2007	102	high level of mixing+ low N_2 sparging	0.56	0.51
30.04.2007	103	high level of mixing+ low N_2 sparging	0.60	0.51
01.05.2007	104	high level of mixing+ low N_2 sparging	0.68	0.69
02.05.2007	105	high level of mixing+ low N_2 sparging	0.68	0.64
03.05.2007	106	high level of mixing+ low N_2 sparging	0.78	0.71
04.05.2007	107	high level of mixing+ low N_2 sparging	0.71	0.69
05.05.2007	108	high level of mixing+ low N_2 sparging	0.72	0.69
06.05.2007	109	high level of mixing+ low N_2 sparging	0.68	0.66
07.05.2007	110	high level of mixing+ low N_2 sparging	0.69	0.59
08.05.2007	111	high level of mixing+ low N_2 sparging	0.72	0.73
09.05.2007	112	high level of mixing+ medium N_2 sparging	0.80	0.76
10.05.2007	113	high level of mixing+ medium N_2 sparging	0.74	0.87
11.05.2007	114	high level of mixing+ medium N_2 sparging	0.68	0.89
12.05.2007	115	high level of mixing+ medium N_2 sparging	0.93	1.21

13.05.2007	116	high level of mixing+ medium N_2 sparging	0.98	1.24
14.05.2007	117	high level of mixing+ medium N_2 sparging	0.92	1.18
15.05.2007	118	high level of mixing+ medium N_2 sparging	0.75	0.89
16.05.2007	119	high level of mixing+ medium N_2 sparging	0.96	1.09
17.05.2007	120	high level of mixing+ medium N_2 sparging	0.73	0.76
18.05.2007	121	high level of mixing+ medium N_2 sparging	0.98	0.80
19.05.2007	122	high level of mixing+ medium N_2 sparging	0.74	0.96
20.05.2007	123	high level of mixing+ medium N_2 sparging	0.76	0.89
21.05.2007	124	high level of mixing+ medium N_2 sparging	0.72	0.88
22.05.2007	125	high level of mixing+ medium N_2 sparging	0.72	0.76
23.05.2007	126	high level of mixing+ medium N_2 sparging	0.83	0.95
24.05.2007	127	high level of mixing+ medium N_2 sparging	0.79	0.86
25.05.2007	128	high level of mixing+ medium N_2 sparging	0.82	1.14
26.05.2007	129	high level of mixing+ medium N_2 sparging	0.70	1.00
27.05.2007	130	high level of mixing+ medium N_2 sparging	0.79	0.93
28.05.2007	131	high level of mixing+ medium N_2 sparging	0.71	0.77
29.05.2007	132	high level of mixing+ medium N_2 sparging	0.67	0.78
30.05.2007	133	high level of mixing+ medium N_2 sparging	0.70	0.88
31.05.2007	134	high level of mixing+ medium N_2 sparging	0.32	0.25
01.06.2007	135	high level of mixing+ medium N_2 sparging	0.88	0.95
02.06.2007	136	high level of mixing+ medium N_2 sparging	0.79	0.94
03.06.2007	137	high level of mixing+ medium N_2 sparging	0.78	1.08
04.06.2007	138	high level of mixing+ medium N_2 sparging	0.83	0.90
05.06.2007	139	high level of mixing+ medium N_2 sparging	0.82	0.89
06.06.2007	140	high level of mixing+ medium N_2 sparging	0.91	0.91
07.06.2007	141	high level of mixing+ medium N_2 sparging	0.83	0.80
08.06.2007	142	high level of mixing+ high N_2 sparging	0.77	0.89
09.06.2007	143	high level of mixing+ high N_2 sparging	0.96	0.89
10.06.2007	144	high level of mixing+ high N_2 sparging	0.96	0.97
11.06.2007	145	high level of mixing+ high N_2 sparging	0.66	0.96
12.06.2007	146	high level of mixing+ high N_2 sparging	0.79	0.90
13.06.2007	147	high level of mixing+ high N_2 sparging	0.85	0.96
14.06.2007	148	high level of mixing+ high N_2 sparging	0.94	0.89
15.06.2007	149	high level of mixing+ high N_2 sparging	0.94	1.01

16.06.2007	150	high level of mixing+ high N_2 sparging	1.08	0.96
17.06.2007	151	high level of mixing+ high N_2 sparging	1.19	0.92
18.06.2007	152	high level of mixing+ high N_2 sparging	1.01	0.81
19.06.2007	153	high level of mixing+ high N_2 sparging	1.07	0.84
20.06.2007	154	high level of mixing+ high N_2 sparging	1.07	0.85
21.06.2007	155	high level of mixing+ high N_2 sparging	1.04	0.86
22.06.2007	156	high level of mixing+ high N_2 sparging	1.07	0.91
23.06.2007	157	high level of mixing+ high N_2 sparging	0.86	0.82
24.06.2007	158	high level of mixing+ high N_2 sparging	0.95	0.96
25.06.2007	159	high level of mixing+ high N_2 sparging	0.94	0.89
26.06.2007	160	high level of mixing+ high N_2 sparging	1.20	0.99
27.06.2007	161	high level of mixing+ high N_2 sparging	0.97	0.88
28.06.2007	162	high level of mixing+ high N_2 sparging	0.91	0.73
29.06.2007	163	high level of mixing+ high N_2 sparging	0.86	0.65
30.06.2007	164	high level of mixing+ high N_2 sparging	0.83	0.85
01.07.2007	165	high level of mixing+ high N_2 sparging	0.85	0.83
02.07.2007	166	high level of mixing+ high N_2 sparging	0.82	0.71
03.07.2007	167	high level of mixing+ high N_2 sparging	0.59	0.98
04.07.2007	168	high level of mixing+ high N_2 sparging	0.96	1.05
05.07.2007	169	high level of mixing+ high N_2 sparging	0.91	0.90

Table 5.C pH, temperature and DO in influent to reactor #1 and #2 (experiment 3, Chapter 5)

		influent reactor #1			influent reactor #2		
Date	Operational conditions	pH	temperature [°C]	DO [mg O_2 l^{-1}]	pH	temperature [°C]	DO [mg O_2 l^{-1}]
17.01.2007	low mixing level	7.00	17.40	2.30	6.90	17.20	2.40
18.01.2007	low mixing level	6.90	17.10	2.60	6.90	17.60	2.60
19.01.2007	low mixing level	6.90	17.10	2.50	6.90	17.40	2.30
20.01.2007	low mixing level	6.72	18.10	2.40	6.77	17.10	2.60
21.01.2007	low mixing level	6.81	14.40	2.00	6.85	17.80	1.90
22.01.2007	low mixing level	7.05	8.60	2.30	6.86	18.50	3.10
23.01.2007	low mixing level	6.93	17.60	2.90	6.83	18.00	2.10
24.01.2007	low mixing level	6.89	17.90	2.80	6.96	18.30	2.70
25.01.2007	low mixing level	6.98	18.30	3.50	7.04	18.10	3.50
26.01.2007	low mixing level	6.90	18.20	3.50	6.92	18.00	3.20
27.01.2007	low mixing level	6.95	21.00	2.50	7.00	19.30	2.40
28.01.2007	low mixing level	7.06	17.30	2.50	7.09	16.90	2.50
29.01.2007	low mixing level	6.95	16.70	3.80	6.89	17.80	2.70
30.01.2007	low mixing level	7.04	16.50	3.10	6.99	16.90	2.90
31.01.2007	low mixing level	7.04	17.70	3.00	6.98	17.60	2.90
01.02.2007	high level of mixing	6.99	19.40	3.40	7.03	18.20	2.90
02.02.2007	high level of mixing	7.06	18.10	3.10	7.00	17.50	3.30
03.02.2007	high level of mixing	7.14	17.10	2.80	6.78	16.00	2.70
04.02.2007	high level of mixing	6.99	17.60	3.20	7.00	16.50	2.70
05.02.2007	high level of mixing	6.96	16.70	3.10	7.00	14.90	3.40
06.02.2007	high level of mixing	7.11	15.80	4.40	7.04	15.40	4.50
07.02.2007	high level of mixing	7.26	18.20	3.60	7.18	17.20	3.40
08.02.2007	high level of mixing	7.10	13.70	4.40	7.00	15.60	3.90
09.02.2007	high level of mixing	7.12	17.30	3.20	7.06	15.90	3.90
10.02.2007	high level of mixing	7.15	18.40	2.60	7.02	17.30	3.30
11.02.2007	high level of mixing	7.16	20.80	2.90	7.05	18.00	3.50
12.02.2007	high level of mixing	7.17	18.40	3.30	7.07	17.60	3.80
13.02.2007	high level of mixing	7.01	18.70	3.50	7.13	17.80	3.10
14.02.2007	high level of mixing	6.97	17.20	3.60	6.95	17.30	3.40
15.02.2007	high level of mixing	7.02	16.50	2.70	6.84	16.70	2.50
16.02.2007	high level of mixing	6.86	16.30	3.00	6.94	17.10	2.10
17.02.2007	medium level of mixing	7.07	21.40	3.20	7.04	19.50	3.00
18.02.2007	medium level of mixing	7.00	18.50	2.50	7.09	17.10	2.90
19.02.2007	medium level of mixing	7.12	18.90	2.70	7.08	18.60	2.50
20.02.2007	medium level of mixing	7.24	18.40	2.50	7.03	18.60	2.60
21.02.2007	medium level of mixing	7.19	19.20	2.30	7.16	18.30	2.70
22.02.2007	medium level of mixing	0.00	0.00	0.00	0.00	0.00	0.00
23.02.2007	medium level of mixing	0.00	0.00	0.00	0.00	0.00	0.00
24.02.2007	medium level of mixing	7.25	19.60	2.40	6.90	18.00	2.60

25.02.2007	medium level of mixing	6.92	20.70	3.60	6.80	18.40	2.10
26.02.2007	medium level of mixing	6.81	22.00	2.60	6.78	19.70	2.30
27.02.2007	medium level of mixing	6.89	20.60	2.40	6.91	19.40	2.80
28.02.2007	medium level of mixing	7.01	20.00	0.60	6.97	19.60	0.20
01.03.2007	medium level of mixing	7.19	19.40	1.00	6.91	18.20	0.30
02.03.2007	medium level of mixing	7.01	19.50	0.60	7.17	18.30	0.10
03.03.2007	medium level of mixing	7.05	21.30	3.50	7.03	19.50	2.90
04.03.2007	medium level of mixing	-	-	-	-	-	-
05.03.2007	medium level of mixing	-	-	-	-	-	-
06.03.2007	medium level of mixing	-	-	-	-	-	-
07.03.2007	medium level of mixing	-	-	-	-	-	-
08.03.2007	medium level of mixing	-	-	-	-	-	-
09.03.2007	medium level of mixing	-	-	-	-	-	-
10.03.2007	medium level of mixing	-	-	-	-	-	-
11.03.2007	medium level of mixing	7.15	21.70	3.40	7.13	19.40	3.30
12.03.2007	medium level of mixing	6.99	21.00	2.90	6.93	19.40	2.90
13.03.2007	medium level of mixing	6.92	19.40	2.90	7.01	20.10	2.70
14.03.2007	medium level of mixing	7.12	20.50	2.70	7.09	19.60	3.00
15.03.2007	medium level of mixing	7.11	18.40	3.60	6.98	18.30	4.10
16.03.2007	medium level of mixing	7.09	18.00	3.80	6.87	17.80	3.30
17.03.2007	medium level of mixing	7.18	21.80	2.80	7.12	19.80	2.90
18.03.2007	medium level of mixing	7.28	21.70	3.20	7.14	19.20	3.30
19.03.2007	medium level of mixing	7.14	19.50	3.10	7.04	19.20	3.70
20.03.2007	medium level of mixing	6.99	18.10	3.70	6.96	18.20	3.20
21.03.2007	medium level of mixing	7.03	19.80	3.00	6.96	18.20	3.20
22.03.2007	medium level of mixing	7.13	19.00	3.50	6.97	18.20	3.90
23.03.2007	medium level of mixing	6.93	19.30	3.80	6.89	18.10	4.10
24.03.2007	medium level of mixing	7.05	20.10	3.10	7.03	18.70	3.10
25.03.2007	medium level of mixing	7.12	21.80	2.20	7.03	21.00	2.30
26.03.2007	medium level of mixing	7.06	20.50	2.40	6.86	20.40	2.50
27.03.2007	medium level of mixing	6.90	24.40	2.50	6.92	21.70	2.30
28.03.2007	medium level of mixing	6.97	19.80	2.40	6.97	19.90	2.10
29.03.2007	medium level of mixing	7.00	19.70	2.90	7.03	18.80	3.50
30.03.2007	medium level of mixing	7.09	19.20	3.60	7.13	19.10	3.90
31.03.2007	medium level of mixing	7.00	19.80	3.10	7.03	19.60	3.40
01.04.2007	medium level of mixing	7.11	19.70	2.20	7.06	18.50	3.40
02.04.2007	medium level of mixing	7.11	19.30	2.90	7.06	18.70	3.40
03.04.2007	high level of mixing+ low N_2 sparging	7.15	18.70	2.40	7.13	20.50	0.20
04.04.2007	high level of mixing+ low N_2 sparging	7.16	21.70	2.20	7.25	19.40	3.00
05.04.2007	high level of mixing+ low N_2 sparging	7.32	19.20	5.00	7.18	19.00	5.00
06.04.2007	high level of mixing+ low N_2 sparging	7.19	19.10	4.10	7.26	18.80	4.70

07.04.2007	high level of mixing+ low N_2 sparging	7.31	19.30	4.10	7.23	19.00	4.60
08.04.2007	high level of mixing+ low N_2 sparging	0.00	0.00	0.00	0.00	0.00	21.90
09.04.2007	high level of mixing+ low N_2 sparging	7.22	20.20	6.10	7.12	19.70	5.20
10.04.2007	high level of mixing+ low N_2 sparging	8.12	20.20	0.40	8.14	20.60	0.50
11.04.2007	high level of mixing+ low N_2 sparging	7.11	19.40	6.60	7.12	19.90	5.90
12.04.2007	high level of mixing+ low N_2 sparging	7.27	20.30	5.50	7.18	20.40	5.00
13.04.2007	high level of mixing+ low N_2 sparging	7.09	20.10	5.10	7.06	20.30	5.00
14.04.2007	high level of mixing+ low N_2 sparging	7.09	20.80	2.10	7.05	21.10	1.80
15.04.2007	high level of mixing+ low N_2 sparging	7.18	21.90	1.80	7.05	21.80	1.50
16.04.2007	high level of mixing+ low N_2 sparging	7.08	21.10	2.20	6.99	20.10	2.00
17.04.2007	high level of mixing+ low N_2 sparging	7.13	20.30	0.90	7.01	19.80	1.60
18.04.2007	high level of mixing+ low N_2 sparging	7.11	20.80	1.70	7.06	20.70	2.30
19.04.2007	high level of mixing+ low N_2 sparging	8.18	21.20	2.10	7.08	21.30	2.00
20.04.2007	high level of mixing+ low N_2 sparging	7.19	20.60	1.20	7.13	20.00	1.40
21.04.2007	high level of mixing+ low N_2 sparging	7.04	24.00	1.40	7.03	23.70	1.30
22.04.2007	high level of mixing+ low N_2 sparging	7.05	22.30	1.70	6.94	22.10	1.30
23.04.2007	high level of mixing+ low N_2 sparging	7.07	21.80	2.20	6.96	21.80	1.20
24.04.2007	high level of mixing+ low N_2 sparging	6.95	20.50	1.30	6.96	19.10	1.80
25.04.2007	high level of mixing+ low N_2 sparging	7.14	21.90	2.00	7.04	21.70	1.70
26.04.2007	high level of mixing+ low N_2 sparging	7.11	22.20	2.30	7.02	22.20	2.00
27.04.2007	high level of mixing+ low N_2 sparging	7.34	22.50	2.60	7.07	21.60	2.10
28.04.2007	high level of mixing+ low N_2 sparging	7.16	21.90	2.20	6.98	21.70	1.90
29.04.2007	high level of mixing+ low N_2 sparging	7.21	21.60	2.20	7.02	21.80	1.60
30.04.2007	high level of mixing+ low N_2 sparging	7.01	21.90	2.30	6.97	19.90	1.90
01.05.2007	high level of mixing+ low N_2 sparging	6.91	21.50	3.00	6.90	21.50	2.20
02.05.2007	high level of mixing+ low N_2 sparging	7.05	21.00	2.00	6.95	21.50	1.30

03.05.2007	high level of mixing+ low N_2 sparging	7.24	21.30	0.30	7.08	20.50	1.40
04.05.2007	high level of mixing+ low N_2 sparging	7.21	21.30	1.90	7.13	22.20	1.10
05.05.2007	high level of mixing+ low N_2 sparging	6.98	21.40	2.20	6.98	21.40	2.30
06.05.2007	high level of mixing+ low N_2 sparging	7.07	22.40	2.10	6.95	21.40	1.70
07.05.2007	high level of mixing+ low N_2 sparging	7.09	22.00	2.10	6.99	22.10	1.80
08.05.2007	high level of mixing+ low N_2 sparging	7.16	21.20	2.20	7.00	20.90	2.00
09.05.2007	high level of mixing+ medium N_2 sparging	7.03	22.60	2.30	7.10	22.10	1.80
10.05.2007	high level of mixing+ medium N_2 sparging	7.41	21.50	2.70	7.28	21.10	2.20
11.05.2007	high level of mixing+ medium N_2 sparging	7.30	20.90	3.00	7.13	20.90	2.70
12.05.2007	high level of mixing+ medium N_2 sparging	7.24	21.00	1.80	7.23	20.90	2.00
13.05.2007	high level of mixing+ medium N_2 sparging	7.07	20.90	2.20	7.11	21.00	2.10
14.05.2007	high level of mixing+ medium N_2 sparging	7.00	21.20	2.80	6.98	21.20	2.90
15.05.2007	high level of mixing+ medium N_2 sparging	7.00	21.80	2.70	7.00	21.40	2.20
16.05.2007	high level of mixing+ medium N_2 sparging	7.00	22.90	2.50	7.00	21.80	1.90
17.05.2007	high level of mixing+ medium N_2 sparging	6.90	21.60	1.90	6.90	18.90	2.10
18.05.2007	high level of mixing+ medium N_2 sparging	6.80	21.10	2.80	6.80	21.60	2.90
19.05.2007	high level of mixing+ medium N_2 sparging	7.13	21.30	1.50	7.07	21.40	2.00
20.05.2007	high level of mixing+ medium N_2 sparging	7.16	21.20	2.40	7.06	21.30	2.30
21.05.2007	high level of mixing+ medium N_2 sparging	7.20	21.10	2.00	7.09	21.20	1.80
22.05.2007	high level of mixing+ medium N_2 sparging	7.19	22.00	2.00	7.02	21.70	2.10
23.05.2007	high level of mixing+ medium N_2 sparging	7.06	19.80	2.00	7.01	21.40	1.50
24.05.2007	high level of mixing+ medium N_2 sparging	7.25	21.40	2.10	7.09	19.20	3.40
25.05.2007	high level of mixing+ medium N_2 sparging	6.61	21.00	2.00	6.74	19.80	2.50
26.05.2007	high level of mixing+ medium N_2 sparging	7.04	21.30	3.10	7.04	20.40	2.60
27.05.2007	high level of mixing+ medium N_2 sparging	7.46	21.20	2.20	7.18	21.00	2.10
28.05.2007	high level of mixing+ medium N_2 sparging	7.22	21.80	2.90	7.18	21.80	3.10

29.05.2007	high level of mixing+ medium N_2 sparging	7.37	21.90	1.60	7.30	21.30	1.30
30.05.2007	high level of mixing+ medium N_2 sparging	7.23	22.10	2.00	7.26	21.90	3.40
31.05.2007	high level of mixing+ medium N_2 sparging	7.36	22.70	1.70	7.25	22.10	1.60
01.06.2007	high level of mixing+ medium N_2 sparging	7.20	23.80	1.80	7.25	21.60	2.50
02.06.2007	high level of mixing+ medium N_2 sparging	7.25	22.50	2.10	7.21	21.90	2.40
03.06.2007	high level of mixing+ medium N_2 sparging	7.19	23.60	2.20	7.16	22.20	2.30
04.06.2007	high level of mixing+ medium N_2 sparging	7.08	22.60	2.30	7.19	22.20	2.20
05.06.2007	high level of mixing+ medium N_2 sparging	7.26	22.50	2.00	7.21	21.40	2.30
06.06.2007	high level of mixing+ medium N_2 sparging	7.20	22.20	2.50	7.18	21.50	2.10
07.06.2007	high level of mixing+ medium N_2 sparging	7.28	22.00	2.10	7.28	22.20	2.30
08.06.2007	high level of mixing+ high N_2 sparging	7.26	21.10	2.60	7.13	21.50	2.20
09.06.2007	high level of mixing+ high N_2 sparging	7.07	23.20	1.70	7.06	22.10	1.60
10.06.2007	high level of mixing+ high N_2 sparging	6.97	23.50	2.40	7.01	22.60	2.10
11.06.2007	high level of mixing+ high N_2 sparging	7.07	22.00	2.50	7.00	21.80	2.40
12.06.2007	high level of mixing+ high N_2 sparging	7.23	22.30	2.30	7.28	21.90	1.70
13.06.2007	high level of mixing+ high N_2 sparging	7.18	21.60	2.40	7.15	21.30	1.90
14.06.2007	high level of mixing+ high N_2 sparging	7.00	23.60	2.20	7.11	23.40	1.60
15.06.2007	high level of mixing+ high N_2 sparging	7.18	22.60	1.60	7.50	22.50	1.30
16.06.2007	high level of mixing+ high N_2 sparging	7.03	22.20	1.60	6.97	22.10	1.40
17.06.2007	high level of mixing+ high N_2 sparging	7.00	22.30	1.20	7.03	22.00	1.40
18.06.2007	high level of mixing+ high N_2 sparging	7.00	21.70	2.00	7.32	20.80	1.70
19.06.2007	high level of mixing+ high N_2 sparging	7.26	20.60	1.80	7.00	20.60	1.40
20.06.2007	high level of mixing+ high N_2 sparging	7.26	21.80	1.40	7.00	20.80	1.10
21.06.2007	high level of mixing+ high N_2 sparging	7.20	22.30	0.00	7.10	22.50	0.50
22.06.2007	high level of mixing+ high N_2 sparging	7.40	21.90	0.90	7.00	21.90	0.90
23.06.2007	high level of mixing+ high N_2 sparging	7.20	22.90	1.20	7.24	22.80	1.10

24.06.2007	high level of mixing+ high N_2 sparging	7.26	22.70	1.50	7.23	22.50	1.10
25.06.2007	high level of mixing+ high N_2 sparging	7.31	22.60	1.70	7.28	22.50	1.60
26.06.2007	high level of mixing+ high N_2 sparging	7.38	21.90	2.00	7.37	22.10	1.80
27.06.2007	high level of mixing+ high N_2 sparging	6.89	22.30	1.10	6.91	22.20	1.00
28.06.2007	high level of mixing+ high N_2 sparging	7.06	22.10	3.00	7.05	22.20	2.00
29.06.2007	high level of mixing+ high N_2 sparging	7.95	20.30	3.00	7.89	22.40	2.00
30.06.2007	high level of mixing+ high N_2 sparging	7.00	21.90	2.80	6.97	21.60	2.50
01.07.2007	high level of mixing+ high N_2 sparging	7.61	21.60	3.10	7.79	21.30	2.30
02.07.2007	high level of mixing+ high N_2 sparging	6.98	24.00	1.90	6.91	23.60	1.60
03.07.2007	high level of mixing+ high N_2 sparging	7.02	23.80	2.40	6.89	23.50	2.10
04.07.2007	high level of mixing+ high N_2 sparging	6.81	22.30	0.90	6.84	22.40	0.80
05.07.2007	high level of mixing+ high N_2 sparging	7.00	23.20	0.40	6.89	22.50	1.10

Table 5.D pH, temperature and DO in reactor #1 and #2 (experiment 3, Chapter 5)

		reactor #1			reactor #2		
Date	Operational conditions	pH	temperature [°C]	DO [mg O_2 l^{-1}]	pH	temperature [°C]	DO [mg O_2 l^{-1}]
17.01.2007	low mixing level	8.46	18.1	0.2	8.60	18.7	0.1
18.01.2007	low mixing level	8.1	19.1	0.2	8.11	18.9	0.2
19.01.2007	low mixing level	7.94	17.8	0.1	8.34	17.8	0.1
20.01.2007	low mixing level	8.6	17.5	0.1	8.27	17.9	0.1
21.01.2007	low mixing level	8.5	18.2	0.1	8.19	18.2	0.1
22.01.2007	low mixing level	8.31	19.1	0.2	8.42	19.3	0.2
23.01.2007	low mixing level	8.4	18.8	0.1	8.21	19.1	0.1
24.01.2007	low mixing level	7.42	19.8	0.1	8.47	18.3	0.1
25.01.2007	low mixing level	8.02	20	0.2	8.16	19.2	0.1
26.01.2007	low mixing level	7.96	19.2	0.1	8.19	19.9	0.1
27.01.2007	low mixing level	8.38	21.8	0.2	8.60	20.9	0.1
28.01.2007	low mixing level	8.25	17.6	0.1	8.65	18.1	0.1
29.01.2007	low mixing level	8.56	18	0.2	8.36	18.9	0.1
30.01.2007	low mixing level	7.78	18.1	0.3	7.94	17.8	0.1
31.01.2007	low mixing level	7.82	19.1	0.2	8.30	18.8	0.2
01.02.2007	high level of mixing	8.16	20.7	0.1	7.94	20.3	0.1
02.02.2007	high level of mixing	8.2	19.8	0.2	8.06	19	0.2
03.02.2007	high level of mixing	8.53	18.1	0.1	8.37	18	0.1
04.02.2007	high level of mixing	7.94	18.7	0.2	8.49	18.3	0.1
05.02.2007	high level of mixing	8.44	18.6	0.2	8.60	17	0.1
06.02.2007	high level of mixing	8.46	16.7	0.2	7.92	18	0.1
07.02.2007	high level of mixing	8.51	18.2	0.1	8.19	18.2	0.1
08.02.2007	high level of mixing	8.06	17.9	0.1	7.97	17.7	0.3
09.02.2007	high level of mixing	8.58	19.3	0.1	8.44	19.4	0.1
10.02.2007	high level of mixing	8.56	20.3	0.1	7.87	19.7	0.1
11.02.2007	high level of mixing	8.05	19.5	0.2	8.35	20	0.1
12.02.2007	high level of mixing	8.6	19.1	0.2	8.56	19.7	0.1
13.02.2007	high level of mixing	8.31	20.7	0.1	8.51	20.2	0.2
14.02.2007	high level of mixing	8.28	19	0.1	8.39	19.3	0.1
15.02.2007	high level of mixing	8.28	18.4	0.3	8.48	18.5	0.1
16.02.2007	high level of mixing	8.46	19	0.3	8.36	18.9	0.3
17.02.2007	medium level of mixing	8.63	21.6	0.5	8.15	20.9	0.5
18.02.2007	medium level of mixing	8.41	19.5	0.1	8.59	20.2	0.1
19.02.2007	medium level of mixing	8.72	20.6	0.1	8.11	19.1	0.1
20.02.2007	medium level of mixing	8.64	19.9	0.1	8.06	20.1	0.1
21.02.2007	medium level of mixing	8.42	19.9	0.1	7.82	19.9	0.1
22.02.2007	medium level of mixing	-	-	-	-	-	-
23.02.2007	medium level of mixing	-	-	-	-	-	-
24.02.2007	medium level of mixing	8.16	20.4	0.1	8.02	19.9	0.2
25.02.2007	medium level of mixing	7.75	20.6	0.1	8.33	20.6	0.1

26.02.2007	medium level of mixing	7.85	21.8	0.1	8.04	21.2	0.1
27.02.2007	medium level of mixing	8.03	21	0.1	8.37	20.2	0.1
28.02.2007	medium level of mixing	8.23	21.4	0.1	8.23	21.2	0.1
01.03.2007	medium level of mixing	8.02	20.5	0.1	7.42	20.8	0.1
02.03.2007	medium level of mixing	8.02	20.8	0.1	8.25	20.2	0.1
03.03.2007	medium level of mixing	8.24	21.4	0.1	8.32	20.9	0.1
04.03.2007	medium level of mixing	8.4	20.5	0.3	8.90	21	0.2
05.03.2007	medium level of mixing	8.8	21.6	0.1	8.90	20.7	0.1
06.03.2007	medium level of mixing	8.4	19.5	0.1	9.00	19.1	0.1
07.03.2007	medium level of mixing	9.2	20	0.6	8.60	19.6	0.1
08.03.2007	medium level of mixing	8.2	20.3	0.7	9.20	19.8	0.6
09.03.2007	medium level of mixing	8.3	20.5	0.4	9.10	20.8	0.1
10.03.2007	medium level of mixing	8.2	22.3	0.4	9.10	21.6	0.5
11.03.2007	medium level of mixing	8.04	20.3	0.9	8.72	20.1	0.8
12.03.2007	medium level of mixing	8.31	21.4	0.2	8.19	21.2	0.2
13.03.2007	medium level of mixing	7.92	21.5	0.2	8.57	21.3	0.1
14.03.2007	medium level of mixing	8.24	21.3	0.2	8.69	21.3	0.2
15.03.2007	medium level of mixing	8.82	20.5	0.2	8.71	20.4	0.2
16.03.2007	medium level of mixing	9.01	19.5	0.1	8.72	19.4	0.1
17.03.2007	medium level of mixing	8.61	21.1	0.3	8.57	20.7	0.2
18.03.2007	medium level of mixing	8.81	21	0.2	8.67	20.3	0.2
19.03.2007	medium level of mixing	8.58	20.9	0.1	8.42	20.6	0.1
20.03.2007	medium level of mixing	8.3	19.6	0.1	7.93	19.9	0.2
21.03.2007	medium level of mixing	8.81	21.6	0.1	8.24	21.3	0.1
22.03.2007	medium level of mixing	8.43	20.3	0.2	8.18	20.4	0.2
23.03.2007	medium level of mixing	7.71	20.3	0.2	7.72	20.2	0.2
24.03.2007	medium level of mixing	7.81	21.3	0.2	7.89	21.1	0.1
25.03.2007	medium level of mixing	8.03	22.3	0.2	8.21	22.1	0.1
26.03.2007	medium level of mixing	8.33	22	0.1	7.70	21.8	0.1
27.03.2007	medium level of mixing	8.4	21.9	0.2	7.52	21.7	0.1
28.03.2007	medium level of mixing	8.46	21.5	0.2	8.37	20.3	0.1
29.03.2007	medium level of mixing	8.2	21.7	0.1	7.79	21	0.2
30.03.2007	medium level of mixing	9.01	21.1	0.2	7.75	20.7	0.1
31.03.2007	medium level of mixing	9.03	21.6	0.2	8.40	21.2	0.1
01.04.2007	medium level of mixing	9.06	21.6	0.2	8.58	20.9	0.1
02.04.2007	medium level of mixing	8.79	19.5	0.1	9.51	19.6	0.1
03.04.2007	high level of mixing+ low N_2 sparging	8.84	21	0.1	8.62	20.5	0.2
04.04.2007	high level of mixing+ low N_2 sparging	9.05	19.4	0.1	9.08	20.9	0.1
05.04.2007	high level of mixing+ low N_2 sparging	9.08	20.3	0.5	8.49	19.6	0.1
06.04.2007	high level of mixing+ low N_2 sparging	9.26	21.3	0.1	9.07	20.8	0.1

07.04.2007	high level of mixing+ low N_2 sparging	9.05	21.9	0.1	8.62	21.2	0
08.04.2007	high level of mixing+ low N_2 sparging	-	21.9	-	-	-	-
09.04.2007	high level of mixing+ low N_2 sparging	7.3	21.3	0.2	8.69	20.9	0
10.04.2007	high level of mixing+ low N_2 sparging	9.08	21.1	0	9.24	21.3	0.3
11.04.2007	high level of mixing+ low N_2 sparging	8.84	22.3	0	8.52	22.4	0.4
12.04.2007	high level of mixing+ low N_2 sparging	8.75	22.6	0.4	8.60	22.5	0.4
13.04.2007	high level of mixing+ low N_2 sparging	8.63	22	0.2	8.66	22	0.2
14.04.2007	high level of mixing+ low N_2 sparging	8.41	23	0.2	8.63	23	0
15.04.2007	high level of mixing+ low N_2 sparging	8.4	23	0	8.43	23.3	0
16.04.2007	high level of mixing+ low N_2 sparging	8.52	21	0	8.73	22.1	0
17.04.2007	high level of mixing+ low N_2 sparging	8.45	22.8	0.2	8.92	22.7	0
18.04.2007	high level of mixing+ low N_2 sparging	8.56	21.8	0	8.80	22.1	0
19.04.2007	high level of mixing+ low N_2 sparging	8.57	22	0	8.62	23.1	0
20.04.2007	high level of mixing+ low N_2 sparging	8.63	23.8	0	8.45	23.7	0
21.04.2007	high level of mixing+ low N_2 sparging	8.37	24.4	0	8.49	24.7	0
22.04.2007	high level of mixing+ low N_2 sparging	8.42	23.6	0	8.34	23.5	0
23.04.2007	high level of mixing+ low N_2 sparging	8.51	23.1	0	8.37	23.5	0
24.04.2007	high level of mixing+ low N_2 sparging	7.56	20.2	0	7.73	21.5	0
25.04.2007	high level of mixing+ low N_2 sparging	7.8	23.4	0	8.70	23.7	0
26.04.2007	high level of mixing+ low N_2 sparging	7.25	23.8	0	8.67	23.7	0
27.04.2007	high level of mixing+ low N_2 sparging	8.09	22.9	0	8.83	23.6	0
28.04.2007	high level of mixing+ low N_2 sparging	7.65	23	0	8.66	23.9	0
29.04.2007	high level of mixing+ low N_2 sparging	7.74	24	0	8.91	24.8	0
30.04.2007	high level of mixing+ low N_2 sparging	8.65	22.2	0	8.57	23.2	0
01.05.2007	high level of mixing+ low N_2 sparging	8.54	22.4	0	8.46	23.3	0
02.05.2007	high level of mixing+ low N_2 sparging	8.64	23	0.1	8.76	23.2	0

03.05.2007	high level of mixing+ low N_2 sparging	8.84	22.2	0	8.88	23.5	0
04.05.2007	high level of mixing+ low N_2 sparging	8.73	22.9	0	8.78	23.5	0
05.05.2007	high level of mixing+ low N_2 sparging	8.66	22.3	0	8.66	21.9	0
06.05.2007	high level of mixing+ low N_2 sparging	8.91	23	0	8.68	23.2	0
07.05.2007	high level of mixing+ low N_2 sparging	8.64	22.5	0.1	8.55	23.1	0
08.05.2007	high level of mixing+ low N_2 sparging	8.77	22	0	8.87	22.3	0
09.05.2007	high level of mixing+ medium N_2 sparging	8.78	23.2	0	9.19	23.8	0
10.05.2007	high level of mixing+ medium N_2 sparging	8.48	23	0	9.19	23	0
11.05.2007	high level of mixing+ medium N_2 sparging	8.4	22.1	0	9.19	22.1	0
12.05.2007	high level of mixing+ medium N_2 sparging	8.85	21.3	0	9.19	22.4	0
13.05.2007	high level of mixing+ medium N_2 sparging	8.77	21.5	0	8.91	22.4	0
14.05.2007	high level of mixing+ medium N_2 sparging	8.49	21.9	0	8.76	22.2	0
15.05.2007	high level of mixing+ medium N_2 sparging	8.52	21.4	2.2	8.75	21	3.4
16.05.2007	high level of mixing+ medium N_2 sparging	8.61	20.5	0	8.72	21.2	0
17.05.2007	high level of mixing+ medium N_2 sparging	8.44	22	0	8.70	19.7	0
18.05.2007	high level of mixing+ medium N_2 sparging	8.55	21.4	0	8.97	21.8	0
19.05.2007	high level of mixing+ medium N_2 sparging	8.42	21.7	0	8.91	22.8	0
20.05.2007	high level of mixing+ medium N_2 sparging	8.46	21.8	0	8.81	22.9	0
21.05.2007	high level of mixing+ medium N_2 sparging	8.5	22.1	2	8.89	22.2	0
22.05.2007	high level of mixing+ medium N_2 sparging	8.55	21.5	0	8.77	22.6	0
23.05.2007	high level of mixing+ medium N_2 sparging	8.54	20.2	0	8.86	21.1	0
24.05.2007	high level of mixing+ medium N_2 sparging	8.72	21.5	0	8.81	22.4	0
25.05.2007	high level of mixing+ medium N_2 sparging	8.72	21.5	0	8.88	22	0
26.05.2007	high level of mixing+ medium N_2 sparging	8.62	23	0	8.98	23.4	0
27.05.2007	high level of mixing+ medium N_2 sparging	8.82	21.3	0	9.12	23.1	0
28.05.2007	high level of mixing+ medium N_2 sparging	8.5	22.2	0	8.80	22.8	0

29.05.2007	high level of mixing+ medium N_2 sparging	8.52	22	0	8.78	21.5	0
30.05.2007	high level of mixing+ medium N_2 sparging	8.37	22.1	0	8.66	22.2	0
31.05.2007	high level of mixing+ medium N_2 sparging	8.62	21.8	0	8.82	23.1	0
01.06.2007	high level of mixing+ medium N_2 sparging	8.8	23	0	8.95	22	1.8
02.06.2007	high level of mixing+ medium N_2 sparging	8.82	23.1	0	9.14	22.9	0
03.06.2007	high level of mixing+ medium N_2 sparging	8.84	23.4	0	9.00	23.5	0
04.06.2007	high level of mixing+ medium N_2 sparging	8.71	21.4	0	8.88	21.1	3
05.06.2007	high level of mixing+ medium N_2 sparging	8.79	22.5	0	8.94	21.4	0
06.06.2007	high level of mixing+ medium N_2 sparging	8.79	20.9	0	8.89	20.8	0
07.06.2007	high level of mixing+ medium N_2 sparging	8.63	22.4	0	8.80	23.1	0
08.06.2007	high level of mixing+ high N_2 sparging	8.5	21	0	8.95	22.1	0
09.06.2007	high level of mixing+ high N_2 sparging	8.82	22.8	0	9.19	23.4	0
10.06.2007	high level of mixing+ high N_2 sparging	8.99	23.5	0	9.15	23.7	0
11.06.2007	high level of mixing+ high N_2 sparging	8.9	23.3	0	9.05	23.8	0
12.06.2007	high level of mixing+ high N_2 sparging	8.88	22.6	2	8.77	23	0
13.06.2007	high level of mixing+ high N_2 sparging	8.86	23.1	0	8.98	22.3	0
14.06.2007	high level of mixing+ high N_2 sparging	8.92	24.2	0	8.68	23.9	0
15.06.2007	high level of mixing+ high N_2 sparging	9	22.6	0	8.90	22.4	0
16.06.2007	high level of mixing+ high N_2 sparging	9.13	24	0.1	9.11	23.6	0
17.06.2007	high level of mixing+ high N_2 sparging	9.17	23.5	0	9.06	23.3	0
18.06.2007	high level of mixing+ high N_2 sparging	8.92	22	0	8.85	23	0
19.06.2007	high level of mixing+ high N_2 sparging	8.96	21	0	8.86	22.1	0
20.06.2007	high level of mixing+ high N_2 sparging	9.07	20	0	9.06	22.5	0
21.06.2007	high level of mixing+ high N_2 sparging	9.13	22.6	0	8.96	22.6	0
22.06.2007	high level of mixing+ high N_2 sparging	9.17	22.3	0	8.60	22.1	0
23.06.2007	high level of mixing+ high N_2 sparging	8.69	23.9	0	8.75	23.2	0

24.06.2007	high level of mixing+ high N_2 sparging	8.82	24.4	0	8.91	23.7	0
25.06.2007	high level of mixing+ high N_2 sparging	0	23	0	0.00	22.9	0
26.06.2007	high level of mixing+ high N_2 sparging	8.94	22.5	0	8.85	22.6	0
27.06.2007	high level of mixing+ high N_2 sparging	8.85	22.9	0.1	8.85	22.9	0.1
28.06.2007	high level of mixing+ high N_2 sparging	8.95	23	0.3	8.78	22.9	0.2
29.06.2007	high level of mixing+ high N_2 sparging	8.93	24.1	0	8.91	24.1	0.1
30.06.2007	high level of mixing+ high N_2 sparging	8.85	23.5	0.1	8.83	23.2	0.1
01.07.2007	high level of mixing+ high N_2 sparging	8.77	23	0.1	8.75	22.8	0.1
02.07.2007	high level of mixing+ high N_2 sparging	8.83	24.9	0	8.59	25.1	0.1
03.07.2007	high level of mixing+ high N_2 sparging	8.87	24.9	0.1	8.82	24.6	0.1
04.07.2007	high level of mixing+ high N_2 sparging	8.83	23.7	0.1	8.98	23.5	0
05.07.2007	high level of mixing+ high N_2 sparging	8.87	24.9	0	8.80	24.9	0

Table 5.E TSS and VSS in the influent to reactor #1 and reactor #2 (experiment 3, Chapter 5)

		reactor #1		reactor #2	
Date	day of the experiment	TSS	VSS	TSS	VSS
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
01.02.2007	16	22.50	17.50	22.43	16.12
02.02.2007	17	21.50	21.00	20.00	18.00
03.02.2007	18	30.50	24.50	45.27	45.27
04.02.2007	19	16.00	13.00	19.50	14.00
05.02.2007	20	18.00	14.00	36.00	25.00
06.02.2007	21	19.00	10.00	32.00	22.00
07.02.2007	22	21.00	15.50	54.00	34.50
08.02.2007	23	34.91	19.99	30.50	13.50
09.02.2007	24	30.00	22.00	75.62	53.73
10.02.2007	25	66.00	30.00	149.00	64.00
11.02.2007	26	27.40	18.93	7.50	7.00
12.02.2007	27	34.81	14.43	28.00	15.50
13.02.2007	28	17.50	8.00	51.43	34.61
14.02.2007	29	18.00	8.00	17.50	16.00
15.02.2007	30	13.50	10.50	28.85	25.37
16.02.2007	31	16.50	13.00	55.72	37.81
17.02.2007	32	23.50	13.50	34.33	21.89
18.02.2007	33	11.00	10.00	17.53	13.40
19.02.2007	34	13.00	13.00	24.90	15.92
20.02.2007	35	29.00	14.00	27.86	13.93
21.02.2007	36	74.00	71.00	76.00	76.00
22.02.2007	37	-	-	-	-
23.02.2007	38	-	-	-	-
24.02.2007	39	-	-	31.00	28.00
25.02.2007	40	2.49	2.49	7.88	7.88
26.02.2007	41	5.86	2.76	7.00	4.67
27.02.2007	42	7.50	5.00	8.50	5.00
28.02.2007	43	16.67	11.33	32.00	26.67
01.03.2007	44	108.33	95.00	40.00	32.86
02.03.2007	45	35.77	29.27	165.85	139.02
03.03.2007	46	-	-	-	-
04.03.2007	47	-	-	-	-
05.03.2007	48	-	-	-	-
06.03.2007	49	-	-	-	-
07.03.2007	50	-	-	-	-
08.03.2007	51	-	-	-	-
09.03.2007	52	-	-	-	-
10.03.2007	53	-	-	-	-
11.03.2007	54	-	-	-	-

12.03.2007	55	9.00	5.50	2.50	2.50
13.03.2007	56	1.50	1.50	2.50	2.50
14.03.2007	57	7.50	6.00	11.62	9.60
15.03.2007	58	6.97	2.49	8.50	4.50
16.03.2007	59	3.33	2.00	6.50	6.00
17.03.2007	60	3.50	3.50	3.50	3.50
18.03.2007	61	1.99	1.49	2.51	1.51
19.03.2007	62	7.36	2.09	7.39	2.66
20.03.2007	63	0.77	0.44	3.60	1.32
21.03.2007	64	1.85	1.85	2.90	2.90
22.03.2007	65	4.18	3.77	4.00	2.14
23.03.2007	66	9.36	0.99	4.37	1.98
24.03.2007	67	6.40	5.20	4.40	2.40
25.03.2007	68	2.33	2.33	2.66	2.66
26.03.2007	69	1.00	1.00	1.67	1.67
27.03.2007	70	2.50	0.50	4.50	2.00
28.03.2007	71	0.93	0.31	2.07	1.03
29.03.2007	72	3.89	1.77	7.46	4.48
30.03.2007	73	1.97	1.64	3.67	3.33
31.03.2007	74	3.33	1.67	2.67	1.67
01.04.2007	75	2.67	1.67	2.33	1.67
02.04.2007	76	3.00	2.33	3.33	2.67
03.04.2007	77	3.17	0.40	2.93	1.26
04.04.2007	78	2.00	-	3.00	-
05.04.2007	79	1.20	0.80	2.00	0.00
06.04.2007	80	3.07	2.05	3.33	1.33
07.04.2007	81	3.00	2.00	7.00	2.00
08.04.2007	82	4.85	4.85	1.42	1.42
09.04.2007	83	7.96	4.48	5.00	1.50
10.04.2007	84	3.86	3.16	3.00	2.33
11.04.2007	85	4.98	4.98	5.00	5.00
12.04.2007	86	3.50	3.50	5.00	4.50
13.04.2007	87	0.99	0.99	2.34	1.67
14.04.2007	88	24.00	16.00	2.67	2.67
15.04.2007	89	2.23	1.86	2.00	0.67
16.04.2007	90	3.00	1.33	2.67	1.33
17.04.2007	91	2.43	2.43	1.71	1.71
18.04.2007	92	1.50	1.50	4.98	4.98
19.04.2007	93	16.00	14.00	5.00	5.00
20.04.2007	94	2.99	1.49	3.00	2.00
21.04.2007	95	3.00	2.50	2.00	1.00
22.04.2007	96	4.00	3.00	4.46	4.46
23.04.2007	97	3.02	2.51	2.00	0.00
24.04.2007	98	2.49	2.00	1.00	1.00

25.04.2007	99	1.50	1.00	1.00	1.00
26.04.2007	100	11.88	5.94	2.50	1.50
27.04.2007	101	4.00	4.00	4.00	4.00
28.04.2007	102	5.45	4.46	2.50	-
29.04.2007	103	1.50	2.50	2.50	2.50
30.04.2007	104	2.50	2.50	4.50	4.50
01.05.2007	105	4.00	3.50	5.00	4.00
02.05.2007	106	1.50	0.50	2.00	2.00
03.05.2007	107	13.00	12.00	-	-
04.05.2007	108	3.31	3.31	3.50	2.50
05.05.2007	109	0.50	0.50	1.00	1.00
06.05.2007	110	2.50	0.50	2.49	2.49
07.05.2007	111	3.50	3.50	2.50	2.50
08.05.2007	112	3.00	2.00	3.50	3.50
09.05.2007	113	4.00	4.00	2.50	2.50
10.05.2007	114	3.00	3.00	5.50	5.50
11.05.2007	115	1.50	1.50	0.99	0.99
12.05.2007	116	1.00	0.50	10.92	2.98
13.05.2007	117	3.75	3.50	1.75	1.75
14.05.2007	118	6.67	3.00	3.67	1.50
15.05.2007	119	7.50	6.00	5.25	4.00
16.05.2007	120	4.25	3.50	4.75	5.00
17.05.2007	121	4.89	4.89	5.25	4.50
18.05.2007	122	3.50	3.50	1.50	1.50
19.05.2007	123	2.50	2.50	3.00	3.00
20.05.2007	124	2.50	2.50	3.50	3.50
21.05.2007	125	3.04	0.71	3.30	0.51
22.05.2007	126	7.07	4.68	5.12	2.94
23.05.2007	127	2.69	1.95	2.23	0.99
24.05.2007	128	4.04	2.76	3.01	2.70
25.05.2007	129	2.50	1.00	6.50	2.00
26.05.2007	130	16.00	12.00	0.50	0.50
27.05.2007	131	4.75	4.00	4.25	3.50
28.05.2007	132	6.50	6.25	21.25	8.00
29.05.2007	133	5.50	4.25	5.50	5.00
30.05.2007	134	12.75	4.50	7.66	1.75
31.05.2007	135	4.50	1.25	7.00	2.00
01.06.2007	136	4.50	-	-	-
02.06.2007	137	6.50	2.00	4.00	1.50
03.06.2007	138	4.00	2.50	4.75	4.25
04.06.2007	139	4.25	3.25	4.75	4.00
05.06.2007	140	3.00	3.00	4.50	4.50
06.06.2007	141	2.75	1.00	3.25	2.50
07.06.2007	142	5.00	3.50	5.00	4.00

08.06.2007	143	1.00	-	-	-
09.06.2007	144	0.50	3.50	4.00	4.00
10.06.2007	145	6.00	2.25	2.75	2.50
11.06.2007	146	45.00	25.50	2.75	2.75
12.06.2007	147	3.25	3.50	2.00	2.00
13.06.2007	148	3.75	0.75	3.75	0.00
14.06.2007	149	7.00	2.00	6.00	2.00
15.06.2007	150	4.50	3.50	2.00	2.00
16.06.2007	151	8.00	7.50	2.50	2.50
17.06.2007	152	5.50	5.50	8.00	5.75
18.06.2007	153	0.50	0.25	1.50	1.50
19.06.2007	154	5.50	2.50	4.50	3.00
20.06.2007	155	6.00	5.00	5.00	6.25
21.06.2007	156	1.00	0.50	0.00	0.00
22.06.2007	157	5.00	0.50	5.00	-
23.06.2007	158	5.00	2.00	4.50	2.00
24.06.2007	159	11.00	11.00	7.75	7.75
25.06.2007	160	3.00	3.00	2.75	2.75
26.06.2007	161	11.50	4.50	9.00	4.50
27.06.2007	162	0.00	0.00	5.93	-
28.06.2007	163	27.50	16.75	6.07	1.82
29.06.2007	164	5.00	3.50	6.00	5.00
30.06.2007	165	6.00	6.00	8.00	8.00
01.07.2007	166	5.47	0.50	5.94	0.50
02.07.2007	167	9.06	3.97	6.67	2.33
03.07.2007	168	8.00	6.25	6.75	4.50
04.07.2007	169	8.63	4.94	4.77	3.80
05.07.2007	170	4.50	2.50	1.75	2.25

Table 5.F TSS and VSS concentration in the effluent from reactor #1 and #2 (experiment 3, Chapter 5)

		reactor #1		reactor #2	
Date	day of the experiment	TSS	VSS	TSS	VSS
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
01.02.2007	16	22.50	17.50	22.43	16.12
02.02.2007	17	21.50	21.00	20.00	18.00
03.02.2007	18	30.50	24.50	45.27	45.27
04.02.2007	19	16.00	13.00	19.50	14.00
05.02.2007	20	18.00	14.00	36.00	25.00
06.02.2007	21	19.00	10.00	32.00	22.00
07.02.2007	22	21.00	15.50	54.00	34.50
08.02.2007	23	34.91	19.99	30.50	13.50
09.02.2007	24	30.00	22.00	75.62	53.73
10.02.2007	25	66.00	30.00	149.00	64.00
11.02.2007	26	27.40	18.93	7.50	7.00
12.02.2007	27	34.81	14.43	28.00	15.50
13.02.2007	28	17.50	8.00	51.43	34.61
14.02.2007	29	18.00	8.00	17.50	16.00
15.02.2007	30	13.50	10.50	28.85	25.37
16.02.2007	31	16.50	13.00	55.72	37.81
17.02.2007	32	23.50	13.50	34.33	21.89
18.02.2007	33	11.00	10.00	17.53	13.40
19.02.2007	34	13.00	13.00	24.90	15.92
20.02.2007	35	29.00	14.00	27.86	13.93
21.02.2007	36	74.00	71.00	76.00	76.00
22.02.2007	37	-	-	-	-
23.02.2007	38	-	-	-	-
24.02.2007	39	-	-	31.00	28.00
25.02.2007	40	2.49	2.49	7.88	7.88
26.02.2007	41	5.86	2.76	7.00	4.67
27.02.2007	42	7.50	5.00	8.50	5.00
28.02.2007	43	16.67	11.33	32.00	26.67
01.03.2007	44	108.33	95.00	40.00	32.86
02.03.2007	45	35.77	29.27	165.85	139.02
03.03.2007	46	-	-	-	-
04.03.2007	47	-	-	-	-
05.03.2007	48	-	-	-	-
06.03.2007	49	-	-	-	-
07.03.2007	50	-	-	-	-
08.03.2007	51	-	-	-	-
09.03.2007	52	-	-	-	-
10.03.2007	53	-	-	-	-

11.03.2007	54	-	-	-	-
12.03.2007	55	9.00	5.50	2.50	2.50
13.03.2007	56	1.50	1.50	2.50	2.50
14.03.2007	57	7.50	6.00	11.62	9.60
15.03.2007	58	6.97	2.49	8.50	4.50
16.03.2007	59	3.33	2.00	6.50	6.00
17.03.2007	60	3.50	3.50	3.50	3.50
18.03.2007	61	1.99	1.49	2.51	1.51
19.03.2007	62	7.36	2.09	7.39	2.66
20.03.2007	63	0.77	0.44	3.60	1.32
21.03.2007	64	1.85	1.85	2.90	2.90
22.03.2007	65	4.18	3.77	4.00	2.14
23.03.2007	66	9.36	0.99	4.37	1.98
24.03.2007	67	6.40	5.20	4.40	2.40
25.03.2007	68	2.33	2.33	2.66	2.66
26.03.2007	69	1.00	1.00	1.67	1.67
27.03.2007	70	2.50	0.50	4.50	2.00
28.03.2007	71	0.93	0.31	2.07	1.03
29.03.2007	72	3.89	1.77	7.46	4.48
30.03.2007	73	1.97	1.64	3.67	3.33
31.03.2007	74	3.33	1.67	2.67	1.67
01.04.2007	75	2.67	1.67	2.33	1.67
02.04.2007	76	3.00	2.33	3.33	2.67
03.04.2007	77	3.17	0.40	2.93	1.26
04.04.2007	78	2.00	-	3.00	-
05.04.2007	79	1.20	0.80	2.00	0.00
06.04.2007	80	3.07	2.05	3.33	1.33
07.04.2007	81	3.00	2.00	7.00	2.00
08.04.2007	82	4.85	4.85	1.42	1.42
09.04.2007	83	7.96	4.48	5.00	1.50
10.04.2007	84	3.86	3.16	3.00	2.33
11.04.2007	85	4.98	4.98	5.00	5.00
12.04.2007	86	3.50	3.50	5.00	4.50
13.04.2007	87	0.99	0.99	2.34	1.67
14.04.2007	88	24.00	16.00	2.67	2.67
15.04.2007	89	2.23	1.86	2.00	0.67
16.04.2007	90	3.00	1.33	2.67	1.33
17.04.2007	91	2.43	2.43	1.71	1.71
18.04.2007	92	1.50	1.50	4.98	4.98
19.04.2007	93	16.00	14.00	5.00	5.00
20.04.2007	94	2.99	1.49	3.00	2.00
21.04.2007	95	3.00	2.50	2.00	1.00
22.04.2007	96	4.00	3.00	4.46	4.46
23.04.2007	97	3.02	2.51	2.00	0.00

24.04.2007	98	2.49	2.00	1.00	1.00
25.04.2007	99	1.50	1.00	1.00	1.00
26.04.2007	100	11.88	5.94	2.50	1.50
27.04.2007	101	4.00	4.00	4.00	4.00
28.04.2007	102	5.45	4.46	2.50	-
29.04.2007	103	1.50	2.50	2.50	2.50
30.04.2007	104	2.50	2.50	4.50	4.50
01.05.2007	105	4.00	3.50	5.00	4.00
02.05.2007	106	1.50	0.50	2.00	2.00
03.05.2007	107	13.00	12.00	-	-
04.05.2007	108	3.31	3.31	3.50	2.50
05.05.2007	109	0.50	0.50	1.00	1.00
06.05.2007	110	2.50	0.50	2.49	2.49
07.05.2007	111	3.50	3.50	2.50	2.50
08.05.2007	112	3.00	2.00	3.50	3.50
09.05.2007	113	4.00	4.00	2.50	2.50
10.05.2007	114	3.00	3.00	5.50	5.50
11.05.2007	115	1.50	1.50	0.99	0.99
12.05.2007	116	1.00	0.50	10.92	2.98
13.05.2007	117	3.75	3.50	1.75	1.75
14.05.2007	118	6.67	3.00	3.67	1.50
15.05.2007	119	7.50	6.00	5.25	4.00
16.05.2007	120	4.25	3.50	4.75	5.00
17.05.2007	121	4.89	4.89	5.25	4.50
18.05.2007	122	3.50	3.50	1.50	1.50
19.05.2007	123	2.50	2.50	3.00	3.00
20.05.2007	124	2.50	2.50	3.50	3.50
21.05.2007	125	3.04	0.71	3.30	0.51
22.05.2007	126	7.07	4.68	5.12	2.94
23.05.2007	127	2.69	1.95	2.23	0.99
24.05.2007	128	4.04	2.76	3.01	2.70
25.05.2007	129	2.50	1.00	6.50	2.00
26.05.2007	130	16.00	12.00	0.50	0.50
27.05.2007	131	4.75	4.00	4.25	3.50
28.05.2007	132	6.50	6.25	21.25	8.00
29.05.2007	133	5.50	4.25	5.50	5.00
30.05.2007	134	12.75	4.50	7.66	1.75
31.05.2007	135	4.50	1.25	7.00	2.00
01.06.2007	136	4.50	-	-	-
02.06.2007	137	6.50	2.00	4.00	1.50
03.06.2007	138	4.00	2.50	4.75	4.25
04.06.2007	139	4.25	3.25	4.75	4.00
05.06.2007	140	3.00	3.00	4.50	4.50
06.06.2007	141	2.75	1.00	3.25	2.50

07.06.2007	142	5.00	3.50	5.00	4.00
08.06.2007	143	1.00	-	-	-
09.06.2007	144	0.50	3.50	4.00	4.00
10.06.2007	145	6.00	2.25	2.75	2.50
11.06.2007	146	45.00	25.50	2.75	2.75
12.06.2007	147	3.25	3.50	2.00	2.00
13.06.2007	148	3.75	0.75	3.75	0.00
14.06.2007	149	7.00	2.00	6.00	2.00
15.06.2007	150	4.50	3.50	2.00	2.00
16.06.2007	151	8.00	7.50	2.50	2.50
17.06.2007	152	5.50	5.50	8.00	5.75
18.06.2007	153	0.50	0.25	1.50	1.50
19.06.2007	154	5.50	2.50	4.50	3.00
20.06.2007	155	6.00	5.00	5.00	6.25
21.06.2007	156	1.00	0.50	0.00	0.00
22.06.2007	157	5.00	0.50	5.00	-
23.06.2007	158	5.00	2.00	4.50	2.00
24.06.2007	159	11.00	11.00	7.75	7.75
25.06.2007	160	3.00	3.00	2.75	2.75
26.06.2007	161	11.50	4.50	9.00	4.50
27.06.2007	162	0.00	0.00	5.93	-
28.06.2007	163	27.50	16.75	6.07	1.82
29.06.2007	164	5.00	3.50	6.00	5.00
30.06.2007	165	6.00	6.00	8.00	8.00
01.07.2007	166	5.47	0.50	5.94	0.50
02.07.2007	167	9.06	3.97	6.67	2.33
03.07.2007	168	8.00	6.25	6.75	4.50
04.07.2007	169	8.63	4.94	4.77	3.80
05.07.2007	170	4.50	2.50	1.75	2.25

Table 5.G TCOD and SCOD in influent to reactor #1 and #2 (experiment 3, Chapter 5)

		reactor #1		reactor #2	
Date	day of the experiment	TCOD	SCOD	TCOD	SCOD
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
20.01.2007	4	57.33	63.00	57.67	111.67
17.02.2007	32	65	-	65.50	-
21.02.2007	36	74.5	-	75.00	-
25.02.2007	40	79.5	-	79.00	-
28.02.2007	43	95	-	115.50	-
04.03.2007	47	95.33	84.33	111.67	100.33
09.03.2007	52	74.67	65.00	84.33	77.67
13.03.2007	56	77	-	86.67	-
15.03.2007	58	65.00	63.75	67.67	67.33
19.03.2007	62	64.67	59.00	58.67	65.33
23.03.2007	66	72.67	73.00	73.00	78.33
27.03.2007	70	53.67	54.67	51.33	58.33
31.03.2007	74	41.67	51.33	42.67	51.67
04.04.2007	78	39.33	24.67	40.67	41.33
08.04.2007	82	53.67	59.33	62.33	59.33
12.04.2007	86	69.00	71.00	58.67	66.67
16.04.2007	90	49.67	81.00	66.33	69.00
20.04.2007	94	89.67	68.00	62.33	66.33
24.04.2007	98	59.00	67.33	60.33	69.00
29.04.2007	103	66.67	75.00	61.67	70.33
05.05.2007	109	60.67	73.67	62.33	68.00
09.05.2007	113	63.33	68.33	55.00	53.33
13.05.2007	117	65.00	69.67	65.33	68.00
17.05.2007	121	60.33	53.17	67.33	61.17
21.05.2007	125	49.67	54.33	62.00	51.33
25.05.2007	129	47.17	46.50	60.33	58.50
29.05.2007	133	55.33	54.67	71.17	53.00
03.06.2007	138	50.67	46.33	51.00	50.00
06.06.2007	141	53.83	57.00	55.67	57.50
10.06.2007	145	56.00	53.00	47.00	44.00
13.06.2007	148	55.00	71.33	52.50	50.67
17.06.2007	152	61.17	63.17	60.00	57.67
21.06.2007	156	44.83	45.83	42.00	48.50
25.06.2007	160	48.67	47.67	44.83	53.50
03.07.2007	168	45.17	54.33	44.67	40.33

Table 5.H TCOD and SCOD in effluent from reactor #1 and #2 (experiment 3, Chapter 5)

		reactor #1		reactor #2	
Date	day of the experiment	TCOD	SCOD	TCOD	SCOD
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
20.01.2007	4	82.00	55.75	57.33	58.50
17.02.2007	32	65.00	-	70.00	-
21.02.2007	36	68.50	-	85.00	-
25.02.2007	40	67.00	-	83.00	-
28.02.2007	43	93.50	-	108.00	-
04.03.2007	47	90.67	77.25	101.25	88.75
09.03.2007	52	72.33	72.33	72.33	72.33
13.03.2007	56	79.67	-	103.33	-
15.03.2007	58	52.33	62.00	79.00	86.00
19.03.2007	62	54.00	52.33	61.67	67.67
23.03.2007	66	68.00	68.67	73.67	69.67
27.03.2007	70	53.67	55.33	68.33	55.33
31.03.2007	74	45.67	39.00	54.33	40.00
04.04.2007	78	58.33	48.33	137.00	49.00
08.04.2007	82	50.67	56.33	79.33	67.75
12.04.2007	86	117.67	66.33	160.67	65.00
16.04.2007	90	70.67	59.67	62.00	63.33
20.04.2007	94	54.00	62.00	60.00	67.67
24.04.2007	98	68.33	61.33	70.33	60.33
29.04.2007	103	82.00	71.67	148.67	92.67
05.05.2007	109	65.33	60.00	74.33	77.67
09.05.2007	113	66.33	57.67	190.67	65.00
13.05.2007	117	61.33	68.67	74.33	67.33
17.05.2007	121	65.33	53.17	78.67	52.33
21.05.2007	125	60.33	53.33	58.00	57.00
25.05.2007	129	51.33	45.33	60.67	56.67
29.05.2007	133	53.67	50.67	55.33	62.83
03.06.2007	138	58.00	50.33	59.33	51.00
06.06.2007	141	65.00	56.50	53.67	54.83
10.06.2007	145	51.67	47.00	51.00	51.00
13.06.2007	148	51.50	52.00	52.00	60.17
17.06.2007	152	58.33	60.33	75.67	47.17
21.06.2007	156	95.00	49.67	54.83	48.00
25.06.2007	160	54.67	45.17	79.50	48.33
03.07.2007	168	47.17	45.17	64.00	45.00

Table 5.I Thickness, density (TS and VS) as well as TS/VS ratio of biofilm in reactor #1 (experiment 3, Chapter 5)

Date	Day of the experiment	Average biofilm thickness [µm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS	EPS [mg g VS $^{-1}$]
24.01.2007	7	3845	59	45	0.75	31.98
		1168	63	47	0.74	26.79
		-	35	25	0.71	-
	average	**2507**	**53**	**39**	**0.73**	**29**
	st.dev	**1893**	**15**	**12**	**0.02**	**4**
30.01.2007	14	1264	62	42	0.68	20
		1634	90	65	0.72	36
		-	-	-	-	62
	average	**1449**	**76**	**53**	**0.70**	**39.33**
	st.dev	**262**	**20**	**16**	**0.03**	**21.51**
08.02.2007	23	771	65	33	0.50	138
		1544	30	12	0.40	
	average	**1157**	**48**	**22**	**0.45**	**138**
	st.dev	**547**	**25**	**14**	**0.07**	**-**
13.02.2007	28	610	60	46	0.77	247
		677	73	57	0.77	66
	average	**644**	**67**	**51**	**0.77**	**157**
	st.dev	**48**	**9**	**8**	**0.00**	**128**
1.03.2007	44	818	66	42	0.64	59
		725	67	37	0.55	91
	average	**772**	**66**	**40**	**0.60**	**74.9**
	st.dev	**66**	**0**	**4**	**0.06**	**22.7**
13.03.2007	56	950	81	63	0.77	80
		480	62	41	0.66	162
	average	**715**	**72**	**52**	**0.72**	**121**
	st.dev	**333**	**14**	**15**	**0.08**	**58**
23.03.2007	66	888	44	33	0.75	270
		481	52	40	0.76	117
	average	**685**	**48**	**37**	**0.76**	**193**
	st.dev	**287**	**6**	**5**	**0.01**	**108**
2.04.2007	76	895	49	35	0.71	40
		759	87	55	0.63	-
	average	**827**	**68**	**45**	**0.67**	**40.40**
	st.dev	**96**	**27**	**14**	**0.06**	**-**
9.04.2007	83	582	60	41	0.69	237
		497	63	38	0.61	-
	average	**540**	**62**	**40**	**0.65**	**237.15**
	st.dev	**60**	**2**	**2**	**0.06**	**-**
16.04.2007	90	730	73	57	0.77	85
		655	65	47	0.72	86
	average	**693**	**69**	**52**	**0.75**	**85**

	st.dev	**53**	**6**	**7**	**0.04**	**1**
24.04.2007	98	909	37	24	0.64	99
		325	58	38	0.66	100
	average	**617**	**48**	**31**	**0.65**	**99**
	st.dev	**413**	**15**	**10**	**0.01**	**1**
1.05.2007	105	510	110	87	0.79	48
		865	76	56	0.74	49
	average	**687**	**93**	**71**	**0.76**	**48**
	st.dev	**252**	**24**	**22**	**0.04**	**0**
08.05.2007	112	346	120	88	0.73	11
		703	72	45	0.62	41
	average	**524**	**96**	**66**	**0.68**	**26**
	st.dev	**253**	**34**	**31**	**0.08**	**21**
16.05.2007	120	292	75	65	0.87	36
		752	43	37	0.85	136
	average	**522**	**59**	**51**	**0.86**	**86**
	st.dev	**325**	**22**	**20**	**0.01**	**71**
24.05.2007	128	441	80	50	0.62	50
		575	90	55	0.61	55
	average	**508**	**85**	**52**	**0.62**	**52**
	st.dev	**94**	**7**	**4**	**0.01**	**3**
31.05.2007	135	498	59	33	0.57	30
		587	73	55	0.76	20
	average	**542**	**66**	**44**	**0.66**	**25**
	st.dev	**63**	**10**	**15**	**0.14**	**7**
07.06.2007	142	248	133	64	0.48	17
		409	162	43	0.27	51
	average	**329**	**147**	**54**	**0.38**	**34**
	st.dev	**114**	**20**	**15**	**0.15**	**24**
13.06.2007	148	158	118	80	0.68	56
		454	90	56	0.62	33
	average	**306**	**104**	**68**	**0.65**	**45**
	st.dev	**209**	**20**	**17**	**0.04**	**16**
21.06.2007	156	124	181	88	0.48	57
		688	100	67	0.67	60
	average	**406**	**140**	**77**	**0.58**	**59**
	st.dev	**399**	**57**	**15**	**0.13**	**2**
28.06.2007	163	216	104	71	0.68	64
		302	79	53	0.67	29
	average	**259**	**91**	**62**	**0.68**	**47**
	st.dev	**61**	**17**	**13**	**0.01**	**25**
05.07.2007	170	488	92	59	0.65	51
		73	50	31	0.61	118
	average	**281**	**71**	**45**	**0.63**	**84**
	st.dev	**293**	**30**	**20**	**0.02**	**48**

Table 5.J Thickness, density (TS and VS) as well as TS/VS ratio and EPS content in biofilm in reactor #2 (experiment 3, Chapter 5)

Date	Day of the experiment	Average biofilm thickness [µm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS	EPS [mg g VS $^{-1}$]
24.01.2007	7	1353	33	33	1.00	197
		1699	64	35	0.54	-
		863	130	90	0.69	-
	average	**1305**	**76**	**53**	**0.74**	**197**
	st.dev	**420**	**49**	**32**	**0.74**	**-**
30.01.2007	14	1262	52	40	0.76	75.00
		986	80	50	0.62	145.45
	-	-	-	-	-	69.44
	average	**1124**	**66**	**45**	**0.69**	**96.63**
	st.dev	**195**	**19**	**7**	**0.10**	**42.37**
08.02.2007	23	727	39	21	0.56	255
		772	39	20	0.51	219
	average	**749**	**39**	**21**	**0.53**	**237**
	st.dev	**31**	**0**	**1**	**0.03**	**25**
13.02.2007	28	675	74	57	0.77	49
		752	55	42	0.76	79
	average	**714**	**65**	**50**	**0.77**	**64**
	st.dev	**55**	**14**	**11**	**0.00**	**21**
1.03.2007	44	1025	71	52	0.73	64
		1011	42	27	0.65	100
	average	**1018**	**57**	**40**	**0.69**	**82**
	st.dev	**9**	**20**	**17**	**0.06**	**25**
13.03.2007	56	889	48	39	0.83	127
		845	52	47	0.90	150
	average	**867**	**50**	**43**	**0.87**	**138**
	st.dev	**31**	**3**	**5**	**0.05**	**16**
23.03.2007	66	1374	48	35	0.72	345
		855	50	32	0.65	280
	average	**1115**	**49**	**34**	**0.69**	**312**
	st.dev	**367**	**1**	**2**	**0.05**	**46**
2.04.2007	76	984	63	37	0.59	67
		953	58	47	0.80	57
	average	**968**	**61**	**42**	**0.70**	**62**
	st.dev	**22**	**3**	**7**	**0.15**	**7**
9.04.2007	83	428	69	44	0.64	178
		983	44	35	0.79	344
	average	**706**	**56**	**39**	**0.71**	**261**
	st.dev	**392**	**18**	**7**	**0.11**	**117**
16.04.2007	90	813	67	55	0.82	45
		781	61	43	0.70	41
	average	**797**	**64**	**49**	**0.76**	**43**

	st.dev	**23**	**4**	**9**	**0.09**	**3**
24.04.2007	98	365	74	60	0.81	56
		305	69	50	0.73	62
	average	**335**	**71**	**55**	**0.77**	**59**
	st.dev	**42**	**4**	**7**	**0.06**	**4**
1.05.2007	105	593	85	65	0.76	77
		729	69	54	0.79	46
	average	**661**	**77**	**60**	**0.78**	**61**
	st.dev	**96**	**12**	**8**	**0.02**	**22**
08.05.2007	112	259	115	85	0.74	21
		840	67	52	0.78	97
	average	**549**	**91**	**68**	**0.76**	**59**
	st.dev	**411**	**34**	**24**	**0.03**	**53**
16.05.2007	120	515	73	60	0.82	17
		526	53	40	0.75	67
	average	**520**	**63**	**50**	**0.78**	**42**
	st.dev	**8**	**14**	**14**	**0.05**	**35**
24.05.2007	128	299	207	133	0.65	20
		677	83	49	0.59	33
	average	**488**	**145**	**91**	**0.62**	**27**
	st.dev	**268**	**88**	**60**	**0.04**	**9**
31.05.2007	135	328	136	100	0.74	50
		345	50	43	0.87	103
	average	**336**	**93**	**72**	**0.80**	**76**
	st.dev	**12**	**61**	**40**	**0.09**	**37**
07.06.2007	142	426	93	60	0.64	33
		404	93	50	0.54	60
	average	**415**	**93**	**55**	**0.59**	**47**
	st.dev	**16**	**0**	**7**	**0.08**	**19**
13.06.2007	148	129	222	120	0.54	94
		145	100	68	0.68	184
	average	**137**	**161**	**94**	**0.61**	**139**
	st.dev	**11**	**87**	**37**	**0.10**	**64**
21.06.2007	156	256	200	109	0.55	67
		178	69	40	0.58	29
	average	**217**	**134**	**75**	**0.56**	**48**
	st.dev	**55**	**93**	**49**	**0.02**	**26**
28.06.2007	163	659	74	49	0.66	93
		238	73	45	0.62	166
	average	**449**	**73**	**47**	**0.64**	**130**
	st.dev	**298**	**1**	**3**	**0.03**	**52**
05.07.2007	170	123	239	100	0.42	50
		485	107	63	0.59	51
	average	**304**	**173**	**82**	**0.50**	**50**
	st.dev	**256**	**93**	**26**	**0.12**	**1**

Table 5.K Proteins content (p),carbohydrates content (c) and c/p ratio of biofilm in reactor #1 (experiment 3, Chapter 5)

Date	Day of the experiment	proteins [mg g VS $^{-1}$]	carbohydrates[mg g VS $^{-1}$]	c/p ratio
31.05.2007	135	114	-	-
		38	-	-
	average	**76**	**-**	**-**
	st.dev	**54**	**-**	**-**
07.06.2007	142	89	7	0.08
		75	19	0.25
	average	**82**	**13**	**0.17**
	st.dev	**10**	**8**	**0.12**
13.06.2007	148	279	25	0.09
		310	41	0.13
	average	**294**	**33**	**0.11**
	st.dev	**22**	**11**	**0.03**
21.06.2007	156	274	34	0.12
		445	49	0.11
	average	**359**	**42**	**0.12**
	st.dev	**121**	**11**	**0.01**
28.06.2007	163	98	20	0.20
		111	36	0.32
	average	**105**	**28**	**0.26**
	st.dev	**10**	**12**	**0.09**
05.07.2007	170	51	58	1.14
		118	91	0.77
	average	**85**	**74**	**0.95**
	st.dev	**47**	**23**	**0.26**

Table 5.L Proteins content (p),carbohydrates content (c) and c/p ratio of biofilm in reactor #2 (experiment 3, Chapter 5)

Date	Day of the experiment	proteins [mg g VS $^{-1}$]	carbohydrates[mg g VS $^{-1}$]	c/p ratio
31.05.2007	135	101	-	-
		281	-	-
	average	**191**	-	-
	st.dev	**127**	-	-
07.06.2007	142	118	150	1.27
		57	37	0.65
	average	**88**	**93**	**0.96**
	st.dev	**43**	**80**	**0.44**
13.06.2007	148	236	18	0.08
		162	37	0.23
	average	**199**	**28**	**0.15**
	st.dev	**52**	**13**	**0.11**
21.06.2007	156	155	19	0.13
		174	100	0.57
	average	**165**	**60**	**0.35**
	st.dev	**13**	**57**	**0.32**
28.06.2007	163	81	50	0.61
		91	89	0.98
	average	**86**	**69**	**0.80**
	st.dev	**7**	**27**	**0.26**
05.07.2007	170	72	31	0.43
		58	19	0.33
	average	**65**	**25**	**0.38**
	st.dev	**10**	**8**	**0.07**

Table 5.M Summary of biofilm parameters in reactor #1 (experiment 3, Chapter 5)

			Biofilm density		Biofilm composition				
Date	Day of the experiment	Biofilm thickness	TS	VS	VS/TS ratio	EPS content	Protein content [p]	Carbohydrates content [c]	c/p ratio
		µm	g l^{-1}	g l^{-1}	-	mg (g VS)$^{-1}$	mg (g VS)$^{-1}$	mg (g VS)$^{-1}$	-
24.01.2007		2047	53	39	0.74	29			
30.01.2007		1449	76	53	0.70	39			
08.02.2007		1157	48	22	0.47	138			
13.02.2007		644	67	51	0.77	155			
1.03.2007		772	66	40	0.60	74			
13.03.2007		715	72	52	0.72	120			
23.03.2007		685	48	37	0.76	193			
2.04.2007		827	68	45	0.66	40			
9.04.2007		540	62	40	0.65	237			
16.04.2007		693	69	52	0.75	85			
24.04.2007		617	48	31	0.65	99			
1.05.2007		687	93	71	0.77	49			
08.05.2007		524	96	66	0.69	26			
16.05.2007		522	59	51	0.86	86			
24.05.2007		508	85	52	0.62	52			
31.05.2007		542	66	44	0.67	25	82.08	-	-
07.06.2007		329	147	54	0.37	34	292.28	13.10	0.17
13.06.2007		306	104	68	0.65	45	359.40	33.09	0.11
21.06.2007		406	140	77	0.55	59	104.55	41.62	0.12
28.06.2007		259	91	62	0.68	47	84.51	27.86	0.26
05.07.2007		281	71	45	0.64	84	55.03	74.48	0.77

Table 5.N Summary of biofilm parameters in reactor #2 (experiment 3, Chapter 5)

			Biofilm density			Biofilm composition			
Date	Day of the experiment	Biofilm thickness	TS	VS	VS/TS ratio	EPS content	Protein content [p]	Carbohydrates content [c]	c/p ratio
		μm	g l^{-1}	g l^{-1}	-	mg (g VS)$^{-1}$	mg (g VS)$^{-1}$	mg (g VS)$^{-1}$	-
24.01.2007		1305	76	53	0.74	195			
30.01.2007		1124	66	45	0.68	96			
08.02.2007		749	39	21	0.53	236			
13.02.2007		714	65	50	0.77	64			
1.03.2007		1018	57	40	0.70	81			
13.03.2007		867	50	43	0.87	138			
23.03.2007		1115	49	34	0.69	312			
2.04.2007		968	61	42	0.69	62			
9.04.2007		706	56	39	0.70	261			
16.04.2007		797	64	49	0.76	43			
24.04.2007		335	71	55	0.77	59			
1.05.2007		661	77	60	0.78	61			
08.05.2007		549	91	68	0.75	59			
16.05.2007		520	63	49	0.77	42			
24.05.2007		488	145	91	0.63	27			
31.05.2007		336	93	72	0.77	76	87.57	-	
07.06.2007		415	93	55	0.59	47	198.62	90.69	0.28
13.06.2007		137	161	94	0.58	139	164.65	27.63	0.15
21.06.2007		217	134	75	0.55	48	85.93	59.59	0.31
28.06.2007		449	73	47	0.64	130	65.18	69.33	0.80
05.07.2007		304	173	82	0.47	50	25.48	25.29	0,38

Table 4.A NO_3, NO_2 concentrations in influent and effluent from testing reactor as well as removal rates (experiment 4, Chapter 6)

			influent			effluent			removal rate
date	**day of the experiment**	**operational conditions**	**NO_3 +NO_2**	**NO_3**	**NO_2**	**NO_3 +NO_2**	**NO_3**	**NO_2**	**(at 20° C)**
			mg l^{-1}	**mg l^{-1}**	**mg l^{-1}**	**mg l^{-1}**	**mg l^{-1}**	**mg l^{-1}**	**[g N d^{-1} m^{-2}]**
04.08.2007	1	no mixing	32.60	31.56	1.04	18.10	12.83	5.27	0.58
05.08.2007	2	no mixing	32.20	31.02	1.18	18.80	13.20	5.60	0.53
06.08.2007	3	no mixing	31.20	29.95	1.25	17.70	12.61	5.09	0.54
07.08.2007	4	no mixing	29.50	28.54	0.96	20.60	18.15	2.45	0.35
08.08.2007	5	no mixing	33.50	32.69	0.81	22.30	19.58	2.72	0.47
09.08.2007	6	no mixing	31.70	30.06	1.64	19.00	13.17	5.83	0.54
10.08.2007	7	ultrasound treatment [2x 2 min]	39.70	37.86	1.84	26.80	20.56	6.24	0.54
11.08.2007	7	ultrasound treatment [2x 2 min]	33.70	32.82	0.88	17.20	11.69	5.51	0.68
12.08.2007	8	ultrasound treatment [2x 2 min]	31.30	30.87	0.43	13.60	8.25	5.35	0.73
13.08.2007	8	ultrasound treatment [2x 2 min]	28.20	27.85	0.35	12.50	9.16	3.34	0.67
14.08.2007	9	ultrasound treatment [2x 2 min]	34.30	28.60	5.70	16.10	9.23	6.87	0.79
15.08.2007	10	ultrasound treatment [2x 2 min]	36.40	33.82	2.58	19.20	11.89	7.31	0.77
16.08.2007	11	ultrasound treatment [2x 2 min]	41.50	39.73	1.77	8.10	6.87	1.23	0.47
17.08.2007	12	ultrasound treatment [2x 2 min]	41.60	34.97	6.63	26.00	21.04	4.96	0.73
18.08.2007	13	ultrasound treatment [2x 2 min]	40.50	38.34	2.16	11.90	7.58	4.32	1.30
19.08.2007	14	ultrasound treatment [2x 2 min]	35.90	34.30	1.60	9.99	5.48	4.51	1.12
20.08.2007	14	ultrasound treatment [2x 2 min]	34.40	32.59	1.81	8.35	4.87	3.48	1.12
21.08.2007	15	ultrasound treatment [2x 2 min]	45.50	42.23	3.27	23.00	18.40	4.60	0.98
	15	ultrasound treatment [2x 2 min]	31.30	0.00	0.00	18.70	0.00	0.00	0.55
22.08.2007	16	ultrasound treatment [2x 2 min]	37.10	35.46	1.64	8.67	4.81	3.86	1.20
23.08.2007	17	ultrasound treatment [2x 2 min]	34.70	33.22	1.48	12.00	8.38	3.62	0.87
24.08.2007	18	ultrasound treatment [2x 2 min]	30.80	29.18	1.62	6.75	4.87	1.88	0.94
25.08.2007	19	ultrasound treatment [2x 2 min]	33.40	31.62	1.78	3.99	2.21	1.78	1.17
26.08.2007	20	ultrasound treatment [2x 2 min]	33.90	31.79	2.11	3.03	0.63	2.40	1.25
27.08.2007	21	ultrasound treatment [2x 2 min]	36.10	33.93	2.17	7.07	4.22	2.85	1.25

28.08.2007	22	ultrasound treatment [2x 2 min]	36.80	36.32	0.49	3.11	1.96	1.15	1.08
29.08.2007	23	ultrasound treatment [2x 2 min]	33.50	31.60	1.90	7.77	5.13	2.64	1.08
30.08.2007	24	ultrasound treatment [2x 2 min]	31.10	29.28	1.82	5.52	3.50	2.02	1.13
31.08.2007	25	ultrasound treatment [2x 2 min]	35.30	33.75	1.55	7.73	5.41	2.32	1.19
01.09.2007	26	ultrasound treatment [2x 2 min]	28.10	26.37	1.73	5.07	2.88	2.19	0.97
02.09.2007	27	ultrasound treatment [2x 2 min]	28.30	27.29	1.01	3.40	1.30	2.10	1.06
03.09.2007	28	ultrasound treatment [2x 2 min]	27.50	24.96	2.54	1.78	0.60	1.18	1.11
04.09.2007	29	ultrasound treatment [2x 2 min]	26.90	25.15	1.75	6.83	4.32	2.51	0.85
05.09.2007	30	ultrasound treatment [2x 2 min]	30.60	29.17	1.43	5.28	3.18	2.10	1.08
06.09.2007	31	ultrasound treatment [2x 2 min]	31.60	29.54	2.06	5.55	3.58	1.97	1.14
07.09.2007	32	ultrasound treatment [2x 2 min]	29.40	27.91	1.49	4.73	3.01	1.72	1.04
08.09.2007	33	ultrasound treatment [2x 2 min]	28.40	26.54	1.86	3.27	1.80	1.47	1.08
09.09.2007	34	ultrasound treatment [2x 2 min]	29.70	26.86	2.84	6.53	3.97	2.56	1.02
10.09.2007	35	ultrasound treatment [2x 2 min]	30.00	28.63	1.37	8.22	5.41	2.81	0.93
11.09.2007	36	ultrasound treatment [2x 2 min]	29.70	27.94	1.76	3.26	1.46	1.80	1.15
12.09.2007	37	ultrasound treatment [2x 2 min]	27.80	25.93	1.87	3.06	0.38	2.68	1.08
13.09.2007	38	ultrasound treatment [2x 2 min]	35.40	33.24	2.16	0.66	0.00	0.66	1.55
14.09.2007	39	ultrasound treatment [2x 2 min]	35.60	34.53	1.07	1.58	0.50	1.08	1.47
15.09.2007	40	ultrasound treatment [2x 2 min]	36.20	34.35	1.85	11.50	9.23	2.27	1.06
16.09.2007	41	ultrasound treatment [2x 2 min]	36.30	34.94	1.36	4.97	1.97	3.00	1.28
17.09.2007	42	ultrasound treatment [2x 2 min]	37.00	34.99	2.01	6.93	4.79	2.14	1.23
18.09.2007	43	ultrasound treatment [2x 2 min]	31.50	29.24	2.26	12.30	10.40	1.90	0.82
19.09.2007	44	ultrasound treatment [2x 2 min]	38.60	36.61	1.99	5.11	3.63	1.48	1.40
20.09.2007	45	ultrasound treatment [2x 2 min]	34.90	32.01	2.89	3.35	-0.96	4.31	1.35
21.09.2007	46	ultrasound treatment [2x 2 min]	32.00	28.04	3.96	3.96	2.33	1.63	1.16
22.09.2007	47	ultrasound treatment [2x 2 min]	34.10	32.64	1.46	5.53	3.47	2.06	1.18
23.09.2007	48	ultrasound treatment [2x 2 min]	33.30	32.02	1.28	1.95	1.17	0.78	1.28
24.09.2007	49	ultrasound treatment [2x 2 min]	32.20	31.36	0.84	2.04	1.19	0.85	1.16
25.09.2007	50	ultrasound treatment [2x 2 min]	31.80	29.95	1.85	3.13	0.99	2.14	1.23

26.09.2007	51	ultrasound treatment [2x 2 min]	31.00	30.07	0.93	17.80	13.35	4.45	0.97
27.09.2007	52	ultrasound treatment [2x 2 min]	33.60	32.79	0.81	6.22	4.87	1.35	1.12
28.09.2007	53	ultrasound treatment [2x 2 min]	32.80	32.10	0.70	4.90	3.65	1.25	1.20
29.09.2007	54	ultrasound treatment [2x 2 min]	34.80	33.41	1.39	5.68	4.19	1.49	1.20
30.09.2007	55	ultrasound treatment [2x 2 min]	34.80	33.32	1.48	5.72	3.68	2.04	1.19
01.10.2007	56	ultrasound treatment [2x 2 min]	31.90	30.58	1.32	5.35	2.94	2.41	1.04
02.10.2007	57	ultrasound treatment [2x 2 min]	33.20	30.68	2.52	7.21	5.22	1.99	1.03
03.10.2007	58	ultrasound treatment [2x 2 min]	35.80	33.25	2.55	6.63	4.85	1.78	1.09
04.10.2007	59	ultrasound treatment [2x 2 min]	30.40	28.09	2.31	5.58	3.08	2.50	0.98
05.10.2007	60	ultrasound treatment [2x 2 min]	41.80	38.23	3.57	17.40	11.68	5.72	0.98
06.10.2007	61	ultrasound treatment [2x 2 min]	33.00	30.33	2.67	12.20	8.16	4.04	0.86
07.10.2007	62	ultrasound treatment [2x 2 min]	34.50	31.39	3.11	14.90	10.71	4.19	0.77
08.10.2007	63	ultrasound treatment [2x 2 min]	37.90	34.15	3.75	19.30	14.14	5.16	0.77
09.10.2007	64	ultrasound treatment [2x 2 min]	37.40	31.74	5.66	9.89	6.19	3.70	1.07
10.10.2007	65	ultrasound treatment [2x 2 min]	33.70	29.09	4.61	14.40	9.53	4.87	0.83
11.10.2007	65	ultrasound treatment [2x 2 min]	26.50	25.07	1.43	9.45	6.18	3.27	0.72
12.10.2007	66	ultrasound treatment [2x 2 min]	34.90	33.88	1.02	6.05	3.35	2.70	123
13.10.2007	67	ultrasound treatment [2x 2 min]	37.10	36.20	0.90	7.21	5.39	1.82	1.29
14.10.2007	68	ultrasound treatment [2x 2 min]	36.20	34.19	2.01	6.78	4.54	2.24	1.23
15.10.2007	69	ultrasound treatment [2x 2 min]	36.30	34.24	2.06	8.11	4.44	3.67	1.26

Table 4.B pH, temperature and DO in influent to testing reactor (experiment 4, Chapter 6)

		influent	testing	reactor
Date	Operational conditions	pH	temperature [°C]	DO [mg O_2 l^{-1}]
04.08.2007	no mixing	6.90	22.20	2.60
05.08.2007	no mixing	6.96	22.40	1.70
06.08.2007	no mixing	7.03	22.10	2.10
07.08.2007	no mixing	6.94	21.90	2.00
08.08.2007	no mixing	6.80	22.50	1.60
09.08.2007	no mixing	6.91	22.50	2.10
10.08.2007	ultrasound treatment [2x 2 min]	6.71	22.10	1.90
11.08.2007	ultrasound treatment [2x 2 min]	6.87	22.20	0.20
12.08.2007	ultrasound treatment [2x 2 min]	6.88	21.80	0.20
13.08.2007	ultrasound treatment [2x 2 min]	6.77	22.00	0.20
14.08.2007	ultrasound treatment [2x 2 min]	8.28	22.00	1.40
15.08.2007	ultrasound treatment [2x 2 min]	6.90	21.30	3.20
16.08.2007	ultrasound treatment [2x 2 min]	6.78	21.10	2.50
17.08.2007	ultrasound treatment [2x 2 min]	6.78	20.80	2.40
18.08.2007	ultrasound treatment [2x 2 min]	6.89	21.10	2.50
19.08.2007	ultrasound treatment [2x 2 min]	7.02	21.00	0.50
20.08.2007	ultrasound treatment [2x 2 min]	6.84	21.10	3.10
21.08.2007	ultrasound treatment [2x 2 min]	7.38	21.50	2.00
22.08.2007	ultrasound treatment [2x 2 min]	7.04	21.20	2.80
23.08.2007	ultrasound treatment [2x 2 min]	7.18	21.50	1.50
24.08.2007	ultrasound treatment [2x 2 min]	6.82	21.30	2.20
25.08.2007	ultrasound treatment [2x 2 min]	7.19	20.80	0.50
26.08.2007	ultrasound treatment [2x 2 min]	7.27	21.80	1.90
27.08.2007	ultrasound treatment [2x 2 min]	7.07	21.40	2.10
28.08.2007	ultrasound treatment [2x 2 min]	7.16	21.50	2.20
29.08.2007	ultrasound treatment [2x 2 min]	6.99	21.60	2.50
30.08.2007	ultrasound treatment [2x 2 min]	7.12	21.90	3.10
31.08.2007	ultrasound treatment [2x 2 min]	7.06	21.30	2.40
01.09.2007	ultrasound treatment [2x 2 min]	7.08	22.10	1.90
02.09.2007	ultrasound treatment [2x 2 min]	0.00	0.00	0.00
03.09.2007	ultrasound treatment [2x 2 min]	7.38	20.20	2.50
04.09.2007	ultrasound treatment [2x 2 min]	7.15	21.50	1.50
05.09.2007	ultrasound treatment [2x 2 min]	7.14	21.60	1.90
06.09.2007	ultrasound treatment [2x 2 min]	7.04	21.90	1.60
07.09.2007	ultrasound treatment [2x 2 min]	7.06	21.80	2.60
08.09.2007	ultrasound treatment [2x 2 min]	7.17	21.60	1.90
09.09.2007	ultrasound treatment [2x 2 min]	7.23	21.00	1.60
10.09.2007	ultrasound treatment [2x 2 min]	7.23	20.50	1.40
11.09.2007	ultrasound treatment [2x 2 min]	6.99	21.40	2.10

12.09.2007	ultrasound treatment [2x 2 min]	7.00	20.50	2.00
13.09.2007	ultrasound treatment [2x 2 min]	7.16	20.00	1.20
14.09.2007	ultrasound treatment [2x 2 min]	7.12	21.00	1.90
15.09.2007	ultrasound treatment [2x 2 min]	7.03	21.00	2.00
16.09.2007	ultrasound treatment [2x 2 min]	7.15	21.40	1.20
17.09.2007	ultrasound treatment [2x 2 min]	7.27	20.40	1.00
18.09.2007	ultrasound treatment [2x 2 min]	8.00	21.50	1.80
19.09.2007	ultrasound treatment [2x 2 min]	7.05	21.50	2.10
20.09.2007	ultrasound treatment [2x 2 min]	7.15	21.30	1.20
21.09.2007	ultrasound treatment [2x 2 min]	7.14	21.70	2.20
22.09.2007	ultrasound treatment [2x 2 min]	7.13	20.60	1.20
23.09.2007	ultrasound treatment [2x 2 min]	7.22	21.50	0.90
24.09.2007	ultrasound treatment [2x 2 min]	7.13	21.90	0.90
25.09.2007	ultrasound treatment [2x 2 min]	7.40	21.60	1.00
26.09.2007	ultrasound treatment [2x 2 min]	7.15	21.30	1.60
27.09.2007	ultrasound treatment [2x 2 min]	7.16	21.40	1.50
28.09.2007	ultrasound treatment [2x 2 min]	7.12	21.10	2.00
29.09.2007	ultrasound treatment [2x 2 min]	7.01	21.90	2.00
30.09.2007	ultrasound treatment [2x 2 min]	7.21	21.60	1.40
01.10.2007	ultrasound treatment [2x 2 min]	7.15	21.60	1.60
02.10.2007	ultrasound treatment [2x 2 min]	7.41	21.50	1.70
03.10.2007	ultrasound treatment [2x 2 min]	7.18	18.40	1.70
04.10.2007	ultrasound treatment [2x 2 min]	7.18	20.60	1.40
05.10.2007	ultrasound treatment [2x 2 min]	7.13	20.30	1.60
06.10.2007	ultrasound treatment [2x 2 min]	7.18	20.70	1.60
07.10.2007	ultrasound treatment [2x 2 min]	7.67	20.80	1.40
08.10.2007	ultrasound treatment [2x 2 min]	7.85	21.10	1.50
09.10.2007	ultrasound treatment [2x 2 min]	7.95	19.40	1.70
10.10.2007	ultrasound treatment [2x 2 min]	7.49	20.70	1.50
11.10.2007	ultrasound treatment [2x 2 min]	7.24	20.80	3.30
12.10.2007	ultrasound treatment [2x 2 min]	6.89	21.00	2.10
13.10.2007	ultrasound treatment [2x 2 min]	7.13	21.10	4.50
14.10.2007	ultrasound treatment [2x 2 min]	7.21	21.30	2.70
15.10.2007	ultrasound treatment [2x 2 min]	8.23	21.20	2.70

Table 4.C pH, temperature and DO in the testing reactor (experiment 4, Chapter 6)

		testing reactor		
Date	**Operational conditions**	**pH**	**temperature [°C]**	**DO [mg O_2 l^{-1}]**
04.08.2007	no mixing	7.97	23.40	0.10
05.08.2007	no mixing	8.02	24.00	0.00
06.08.2007	no mixing	7.90	23.60	0.00
07.08.2007	no mixing	7.69	23.70	0.10
08.08.2007	no mixing	7.56	24.40	0.00
09.08.2007	no mixing	7.95	24.10	0.10
10.08.2007	ultrasound treatment [2x 2 min]	7.30	23.00	0.00
11.08.2007	ultrasound treatment [2x 2 min]	8.81	22.70	0.00
12.08.2007	ultrasound treatment [2x 2 min]	8.80	22.20	0,00
13.08.2007	ultrasound treatment [2x 2 min]	8.71	22.70	0.10
14.08.2007	ultrasound treatment [2x 2 min]	9.06	22.90	0.00
15.08.2007	ultrasound treatment [2x 2 min]	8.59	22.30	0.10
16.08.2007	ultrasound treatment [2x 2 min]	9.15	22.00	0.10
17.08.2007	ultrasound treatment [2x 2 min]	8.75	21.70	0.00
18.08.2007	ultrasound treatment [2x 2 min]	8.98	22.00	0.10
19.08.2007	ultrasound treatment [2x 2 min]	9.03	22.30	0.00
20.08.2007	ultrasound treatment [2x 2 min]	8.68	21.90	0.00
21.08.2007	ultrasound treatment [2x 2 min]	9.31	22.20	0.00
22.08.2007	ultrasound treatment [2x 2 min]	9.35	22.40	0.10
23.08.2007	ultrasound treatment [2x 2 min]	9.34	22.70	0.00
24.08.2007	ultrasound treatment [2x 2 min]	9.32	22.30	0.10
25.08.2007	ultrasound treatment [2x 2 min]	9.42	22.00	0.10
26.08.2007	ultrasound treatment [2x 2 min]	9.33	22.40	0.00
27.08.2007	ultrasound treatment [2x 2 min]	9.23	22.40	0.00
28.08.2007	ultrasound treatment [2x 2 min]	9.47	22.20	0.10
29.08.2007	ultrasound treatment [2x 2 min]	9.28	23.00	0.00
30.08.2007	ultrasound treatment [2x 2 min]	9.47	22.90	0.20
31.08.2007	ultrasound treatment [2x 2 min]	9.39	23.10	0.00
01.09.2007	ultrasound treatment [2x 2 min]	9.40	23.10	0.00
02.09.2007	ultrasound treatment [2x 2 min]	0.00	23.00	0.00
03.09.2007	ultrasound treatment [2x 2 min]	9.69	22.80	0.00
04.09.2007	ultrasound treatment [2x 2 min]	9.39	22.90	0.00
05.09.2007	ultrasound treatment [2x 2 min]	9.63	22.90	0.00
06.09.2007	ultrasound treatment [2x 2 min]	9.54	22.50	0.10
07.09.2007	ultrasound treatment [2x 2 min]	9.54	22.70	0.30
08.09.2007	ultrasound treatment [2x 2 min]	9.61	22.60	0.00
09.09.2007	ultrasound treatment [2x 2 min]	9.38	22.50	0.20
10.09.2007	ultrasound treatment [2x 2 min]	9.29	22.90	0.00
11.09.2007	ultrasound treatment [2x 2 min]	9.31	22.90	0.10
12.09.2007	ultrasound treatment [2x 2 min]	9.65	22.60	0.00

13.09.2007	ultrasound treatment [2x 2 min]	9.61	21.60	0.00
14.09.2007	ultrasound treatment [2x 2 min]	9.62	22.00	0.50
15.09.2007	ultrasound treatment [2x 2 min]	9.29	22.50	0.40
16.09.2007	ultrasound treatment [2x 2 min]	9.14	22.60	0.00
17.09.2007	ultrasound treatment [2x 2 min]	9.24	22.90	0.00
18.09.2007	ultrasound treatment [2x 2 min]	9.42	23.00	0.10
19.09.2007	ultrasound treatment [2x 2 min]	9.38	23.00	0.20
20.09.2007	ultrasound treatment [2x 2 min]	9.49	22.90	0.00
21.09.2007	ultrasound treatment [2x 2 min]	9.32	22.90	0.10
22.09.2007	ultrasound treatment [2x 2 min]	9.56	21.80	0.00
23.09.2007	ultrasound treatment [2x 2 min]	9.67	22.30	0.00
24.09.2007	ultrasound treatment [2x 2 min]	9.55	22.90	0.00
25.09.2007	ultrasound treatment [2x 2 min]	9.58	22.60	0.10
26.09.2007	ultrasound treatment [2x 2 min]	9.80	23.00	0.00
27.09.2007	ultrasound treatment [2x 2 min]	9.89	22.80	0.10
28.09.2007	ultrasound treatment [2x 2 min]	9.81	21.50	0.10
29.09.2007	ultrasound treatment [2x 2 min]	9.43	22.00	0.00
30.09.2007	ultrasound treatment [2x 2 min]	9.47	22.60	0.00
01.10.2007	ultrasound treatment [2x 2 min]	9.26	22.30	0.10
02.10.2007	ultrasound treatment [2x 2 min]	9.42	22.60	0.40
03.10.2007	ultrasound treatment [2x 2 min]	9.41	22.60	0.00
04.10.2007	ultrasound treatment [2x 2 min]	9.23	22.60	0.10
05.10.2007	ultrasound treatment [2x 2 min]	9.02	22.20	0.10
06.10.2007	ultrasound treatment [2x 2 min]	9.24	22.70	0.00
07.10.2007	ultrasound treatment [2x 2 min]	9.20	22.30	0.10
08.10.2007	ultrasound treatment [2x 2 min]	9.35	22.50	0.00
09.10.2007	ultrasound treatment [2x 2 min]	9.68	21.00	0.00
10.10.2007	ultrasound treatment [2x 2 min]	9.57	21.90	0.00
11.10.2007	ultrasound treatment [2x 2 min]	9.94	22.30	0.60
12.10.2007	ultrasound treatment [2x 2 min]	9.80	22.50	0.10
13.10.2007	ultrasound treatment [2x 2 min]	9.38	22.60	0.20
14.10.2007	ultrasound treatment [2x 2 min]	9.35	22.60	0.10
15.10.2007	ultrasound treatment [2x 2 min]	9.26	22.60	0.00

Table 4.D TSS and VSS concentrations in influent and effluent from testing reactor (experiment 4, Chapter 6)

Date	day of the experiment	influent		effluent	
		TSS	VSS	TSS	VSS
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
04.08.2007	1	4.50	4.00	22.00	22.00
05.08.2007	2	5.00	3.50	15.50	9.50
06.08.2007	3	6.50	4.00	36.89	29.13
07.08.2007	4	8.75	59.50	23.50	16.50
08.08.2007	5	8.25	7.00	8.25	7.25
09.08.2007	6	5.00	5.00	4.25	5.00
10.08.2007	7	6.00	5.00	3.39	4.16
11.08.2007	7	19.80	13.86	26.00	18.00
12.08.2007	8	111.00	107.00	6.00	8.00
13.08.2007	8	9.50	7.50	4.25	4.25
14.08.2007	9	5.25	3.50	4.25	3.25
15.08.2007	10	3.75	5.25	3.10	4.66
16.08.2007	11	1.75	4.50	14.00	12.00
17.08.2007	12	3.50	1.25	56.50	36.75
18.08.2007	13	2.00	2.50	4.50	3.50
19.08.2007	14	16.00	9.00	12.00	8.00
20.08.2007	14	4.25	4.25	8.25	6.50
21.08.2007	15	12.00	8.50	3.50	3.50
22.08.2007	16	5.75	5.00	10.50	9.00
23.08.2007	17	2.55	1.30	6.00	4.75
24.08.2007	18	16.39	10.00	14.50	9.50
25.08.2007	19	4.50	0.50	8.00	5.50
26.08.2007	20	1.00	2.00	6.00	5.00
27.08.2007	21	3.75	2.75	7.25	5.50
28.08.2007	22	3.00	3.00	10.84	8.37
29.08.2007	23	6.67	3.33	6.00	5.33
30.08.2007	24	3.49	1.74	7.56	5.81
31.08.2007	25	3.50	3.00	9.50	6.50
01.09.2007	26	-2.00	-0.50	8.50	6.50
02.09.2007	27	-	-	-	-
03.09.2007	28	5.45	2.48	14.93	10.45
04.09.2007	29	2.97	0.50	19.00	12.50
05.09.2007	30	0.99	4.46	5.47	6.97
06.09.2007	31	3.00	4.50	40.10	31.68
07.09.2007	32	2.48	2.48	8.42	7.92
08.09.2007	33	4.98	4.48	13.30	11.33
09.09.2007	34	3.50	1.00	8.82	4.41
10.09.2007	35	2.97	2.97	6.90	6.40
11.09.2007	36	5.00	3.00	9.95	7.46

12.09.2007	37	6.50	4.00	19.40	15.42
13.09.2007	38	3.00	1.50	5.94	5.94
14.09.2007	39	5.00	3.00	7.50	5.00
15.09.2007	40	6.44	4.46	31.00	25.00
16.09.2007	41	4.50	4.00	21.00	17.00
17.09.2007	42	4.00	3.00	6.47	4.48
18.09.2007	43	5.00	4.00	13.50	10.00
19.09.2007	44	4.00	4.00	10.89	9.41
20.09.2007	45	2.50	3.00	12.75	9.80
21.09.2007	46	2.99	2.49	6.00	5.50
22.09.2007	47	6.00	4.50	6.50	5.00
23.09.2007	48	4.00	3.50	8.96	7.46
24.09.2007	49	2.48	2.48	4.23	4.23
25.09.2007	50	-	-	-	-
26.09.2007	51	2.50	1.50	44.50	31.50
27.09.2007	52	4.52	3.52	6.00	5,00
28.09.2007	53	3.00	2.50	3.57	2.98
29.09.2007	54	2.00	2.00	7.00	5.50
30.09.2007	55	4.00	1.00	8.00	7.00
01.10.2007	56	4.00	3.50	4.50	2.00
02.10.2007	57	2.99	2.99	4.46	5.45
03.10.2007	58	0.50	2.48	6.37	6.37
04.10.2007	59	1.49	2.97	7.92	6.44
05.10.2007	60	5.45	3.96	3.94	3.94
06.10.2007	61	4.43	5.42	23.00	21.00
07.10.2007	62	8.00	8.50	13.00	11.50
08.10.2007	63	5.45	3.96	4.46	2.48
09.10.2007	64	3.00	2.00	27.72	21.78
10.10.2007	65	6.44	3.47	19.31	12.87
11.10.2007	65	3.43	0.98	18.50	13.50
12.10.2007	66	2.00	1.50	1.99	1.49
13.10.2007	67	4.46	3.47	4.93	3.94
14.10.2007	68	3.98	2.49	5..97	4.48
15.10.2007	69	3.96	2.48	3.47	3.47

Table 4.E TCOD and SCOD concentrations in influent and effluent from testing reactor (experiment 4, Chapter 6)

		influent		effluent	
Date	day of the experiment	TCOD	SCOD	TCOD	SCOD
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
08.08.2007	204	61.83	53.50	59.67	51.67
10.08.2007	206	58.00	44.33	57.00	52.33
11.08.2007	207	55.00	45.67	54.00	48.33
12.08.2007	208	49.00	40.33	53.00	42.00
13.08.2007	209	50.67	49.33	54.33	46.33
14.08.2007	210	64.00	59.67	64.67	53.33
15.08.2007	211	59.33	54.00	68.67	56.33
17.08.2007	213	52.67	48.67	64.00	61.33
18.08.2007	214	51.67	50.67	67.67	67.33
20.08.2007	216	56.00	48.00	57.67	53.33
24.08.2007	220	55.00	58.67	69.67	67.33
26.08.2007	222	50,00	60.33	56.67	56.67
27.08.2007	223	85.33	54.67	69.00	69.33
07.09.2007	234	52.00	50.67	69.67	66.67
08.09.2007	235	55.67	50.00	74.00	63.33
09.09.2007	236	56.67	65.00	118.00	66.67
14.09.2007	241	76.67	74.67	127.67	74.33
15.09.2007	242	76.67	69.33	106.33	78.00
16.09.2007	243	75.67	74.33	150.00	71.00
18.09.2007	245	65.33	63.67	81.00	69.33
21.09.2007	248	57.67	60.00	74.00	66.00
22.09.2007	249	57.33	53.67	78.00	68.00
23.09.2007	250	58.00	60.00	86.00	62.33
01.10.2007	258	56.33	51.00	96.00	92.33
13.10.2007	269	53.00	44.33	58.67	51.33
14.10.2007	270	50.00	36.67	67.00	52.33
15.10.2007	271	37.33	33.33	-	49.67

Table 4.F Thickness, density (TS and VS) as well as TS/VS ratio and EPS content in biofilm in testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	Average biofilm thickness [μm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS	EPS [mg g VS $^{-1}$]
09.08.2007	6	993	76	48	0.63	66.49
		632	67	42	0.63	59.38
	average	**813**	**71**	**45**	**0.63**	**63**
	st.dev	**255**	**6**	**4**	**0.00**	**5**
17.08.2007	12	527	124	70	0.57	36
		57	81	51	0.63	148
	average	**292**	**102**	**60**	**0.60**	**91.72**
	st.dev	**332**	**30**	**14**	**0.04**	**79.21**
23.8.2007	17	79	129	65	0.51	42
		651	55	41	0.75	52
	average	**365**	**92**	**53**	**0.63**	**47**
	st.dev	**404**	**52**	**17**	**0.17**	**7**
30.8.2007	24	239	86	50	0.58	500
		200	67	37	0.55	135
	average	**220**	**76**	**44**	**0.57**	**318**
	st.dev	**28**	**13**	**9**	**0.02**	**258**
06.09.2007	31	347	90	54	0.60	72
		577	213	114	0.54	46
	average	**462**	**151**	**84**	**0.57**	**59.0**
	st.dev	**163**	**87**	**42**	**0.05**	**17.9**
25.09.2007	50	178	86	58	0.68	-
		-	71	41	0.59	-
	average	**178**	**78**	**50**	**0.63**	**-**
	st.dev	**-**	**11**	**12**	**0.07**	**-**
01.10.2007	56	254	139	80	0.58	-
		234	83	45	0.55	-
	average	**244**	**111**	**63**	**0.56**	**-**
	st.dev	**14**	**39**	**24**	**0.02**	**-**
09.10.2007	64	740	94	54	0.58	71
		444	101	46	0.46	62
	average	**592**	**97**	**50**	**0.52**	**66.36**
	st.dev	**209**	**5**	**6**	**0.09**	**6.49**
15.10.2007	69	645	84	53	0.63	0
		635	77	46	0.59	44
	average	**640**	**80**	**49**	**0.61**	**22.05**
	st.dev	**7**	**5**	**5**	**0.02**	**30.90**

Table 4.G Proteins content (p),carbohydrates content (c) and c/p ratio of biofilm in testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	proteins [mg g VS $^{-1}$]	carbohydrates[mg g VS $^{-1}$]	c/p ratio
09.08.2007	6	80	19	0.24
		88	32	0.37
	average	**84**	**26**	**0.30**
	st.dev	**6**	**10**	**0.09**
17.08.2007	12	26	20	0.76
		63	46	0.73
	average	**45**	**33**	**0.75**
	st.dev	**26**	**18**	**0.02**
23.08.2007	17	39	17	0.44
		91	35	0.39
	average	**65**	**26**	**0.41**
	st.dev	**37**	**13**	**0.04**
30.08.2007	24	29	59	2.02
		55	36	0.65
	average	**42**	**47**	**1.33**
	st.dev	**18**	**16**	**0.96**
06.09.2007	31	35	33	0.95
		23	17	0.71
	average	**29**	**25**	**0.83**
	st.dev	**8**	**12**	**0.17**
20.09.2007	45	27	23	0.88
		30	32	1.08
	average	**28**	**28**	**0.98**
	st.dev	**2**	**6**	**0.15**
01.10.2007	56	41	24	0.58
		67	32	0.48
	average	**54**	**28**	**0.53**
	st.dev	**18**	**6**	**0.07**
09.10.2007	64	40	44	1.09
		108	39	0.36
	average	**74**	**41**	**0.72**
	st.dev	**48**	**3**	**0.51**
15.10.2007	69	59	32	0.54
		83	22	0.27
	average	**71**	**27**	**0.41**
	st.dev	**17**	**7**	**0.19**

Table 4.H Summary of biofilm parameters in testing reactor (experiment 4, Chapter 6)

			Biofilm density		Biofilm composition				
Date	Day of the experiment	Biofilm thickness	TS	VS	VS/TS ratio	EPS content	Protein content [p]	Carbohydrates content [c]	c/p ratio
		µm	g l^{-1}	g l^{-1}	-	mg (g VS)$^{-1}$	mg (g VS)$^{-1}$	mg (g VS)$^{-1}$	-
09.08.2007	6	813	71	45	0.63	63	84	26	0.30
17.08.2007	12	292	102	60	0.60	92	45	33	0.75
23.8.2007	17	365	92	53	0.63	47	65	26	0.41
30.8.2007	24	220	76	44	0.57	318	42	47	1.33
06.09.2007	31	462	151	84	0.57	59	29	25	0.83
25.09.2007	50	178	78	50	0.63	-	28	28	0.98
01.10.2007	56	244	111	63	0.56	-	54	28	0.53
09.10.2007	64	592	97	50	0.52	66	74	41	0.72
15.10.2007	69	640	80	49	0.61	22	71	27	0.41

Table 4.I Biofilm viability in testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	viability [%]
04.08.2007	**1**	32
		30
	average	**31**
	st.dev	**1**
25.09.2007	50	10
		9
		12
		19
	average	**13**
	st.dev	**5**
10.10.2007	65	17
		18
		30
	average	**21**
	st.dev	**7**
17.10.2007	71	9
		9
		17
		5
	average	**10**
	st.dev	**5**

Table 4.J NO_3, NO_2 concentrations in influent and effluent from testing and control reactor (experiment 4, Chapter 6)

			testing reactor						control reactor					
			influent			effluent			influent			effluent		
date	day of the experiment	operational conditions	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2	NO_3+NO_2	NO_3	NO_2
			$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$
26.01.2008	1	no shear force	34.00	33.50	0.50	25.20	21.05	4.15	34.10	33.20	0.90	13.70	4.99	8.71
27.01.2008	2	no shear force	35.80	35.10	0.70	25.60	22.22	3.38	33.00	31.71	1.29	19.30	6.10	13.20
28.01.2008	3	no shear force	33.40	32.80	0.60	24.70	23.41	1.29	34.70	31.91	2.79	21.30	7.70	13.60
29.01.2008	4	no shear force	30.40	28.14	2.26	16.70	12.59	4.11	34.60	31.98	2.62	18.40	5.20	13.20
30.01.2008	5	no shear force	31.00	30.20	0.80	21.00	17.85	3.15	30.90	29.56	1.34	17.90	4.60	13.30
31.01.2008	6	no shear force	31.50	30.90	0.60	19.50	15.75	3.75	31.50	29.05	2.45	18.90	3.10	15.80
01.02.2008	7	no shear force	26.70	26.30	0.40	19.00	16.09	2.91	28.60	28.00	0.60	20.40	5.20	15.20
02.02.2008	8	no shear force	35.10	34.59	0.51	21.30	18.28	3.02	39.60	38.93	0.67	22.10	10.60	11.50
03.02.2008	9	no shear force	35.80	35.33	0.47	21.00	17.87	3.13	34.40	33.67	0.73	26.30	10.30	16.00
04.02.2008	10	no shear force	32.40	31.83	0.57	20.00	17.00	3.00	36.30	35.32	0.98	28.30	12.00	16.30
05.02.2008	11	no shear force	34.20	33.72	0.48	24.70	22.77	1.93	4400	35.34	8.66	24.40	6.60	17.80
06.02.2008	12	no shear force	48.00	47.55	0.45	34.20	31.46	2.74	58.20	48.95	9.25	33.80	14.40	19.40
07.02.2008	13	no shear force	34.40	33.86	0.54	26.20	22.19	4.01	46.90	36.00	10.90	33.70	12.70	21.00
08.02.2008	14	no shear force	39.30	39.07	0.23	28.00	24.53	3.47	49.10	38.10	11.00	32.20	13.90	18.30
09.02.2008	15	no shear force	36.10	35.76	0.34	26.30	22.83	3.47	44.70	33.00	11.70	21.70	13.61	8.09
10.02.2008	16	no shear force	34.30	33.84	0.46	24.40	21.29	3.11	44.60	32.40	12.20	23.70	14.55	9.15
11.02.2008	17	no shear force	34.20	33.86	0.34	24.90	21.62	3.28	42.10	31.10	11.00	18.70	10.21	8.49
12.02.2008	18	no shear force	47.40	47.19	0.21	21.20	19.79	1.41	64.90	54.00	10.90	6.32	1.00	5.32
13.02.2008	19	no shear force	33.80	33.50	0.30	22.90	21.17	1.73	42.00	30.20	11.80	21.10	13.39	7.71
14.02.2008	20	no shear force	36.40	36.06	0.34	26.00	24.09	1.91	43.90	32.10	11.80	9.86	4.48	5.38
15.02.2008	21	no shear force	36,60	36.21	0.39	27.00	25.01	1.99	45.10	33.60	11.50	13.70	6.51	7.19
16.02.2008	22	no shear force	37.00	36.64	0.36	28.50	26.38	2.12	43.60	33.30	10.30	19.90	12.14	7.76
17.02.2008	23	no shear force	34.30	33.77	0.53	25.60	23.65	1.95	45.50	33.80	11.70	22.90	13.69	9.21

18.02.2008	24	no shear force	34.60	34.16	0.44	25.30	23.25	2.05	45.60	34.70	10.90	22.90	14.18	8.72
19.02.2008	25	no shear force	32.80	32.38	0.42	18.40	16.18	2.22	43.30	32.60	10.70	13.80	6.35	7.45
20.02.2008	26	no shear force	30.20	29.63	0.57	18.60	15.70	2.90	38.50	28.30	10.20	14.30	6.57	7.73
21.02.2008	27	no shear force	31.80	31.17	0.63	26.60	23.57	3.03	46.60	36.00	10.60	18.50	10.32	8.18
22.02.2008	28	no shear force	28.70	28.36	0.34	24.00	21.46	2.54	33.20	23.00	10.20	20.90	11.65	9.25
23.02.2008	29	no shear force	37.40	36.99	0.41	25.60	22.88	2.72	39.30	37.46	1.84	20.40	16.31	4.09
24.02.2008	30	no shear force	36.60	36.02	0.58	23.80	20.98	2.82	39.80	38.12	1.68	21.70	17.43	4.27
25.02.2008	31	ultrasound treatment [2x 0.25 min]	35.50	35.04	0.46	27.60	24.54	3.06	35.00	31.94	3.06	16.80	13.50	3.30
26.02.2008	32	ultrasound treatment [2x 0.25 min]	46.60	45.97	0.63	27.90	24.69	3.21	41.20	40.42	0.78	10.70	5.43	5.27
27.02.2008	33	ultrasound treatment [2x 0.25 min]	37.50	36.93	0.57	24.90	21.23	3.67	36.20	35.40	0.80	9.48	6.16	3.02
28.02.2008	34	ultrasound treatment [2x 0.25 min]	34.30	33.61	0.69	15.30	12.92	2.38	20.50	19.82	0.68	9.43	6.55	2.88
29.02.2008	35	ultrasound treatment [2x 0.25 min]	34.70	34.34	0.36	23.30	21.61	1.69	39.90	39.31	0.59	13.20	9.68	3.52
01.03.2008	36	ultrasound treatment [2x 0.25 min]	33.00	31.53	1.47	22.40	17.96	4.44	39.10	36.96	2.14	13.70	8.54	5.16
02.03.2008	37	ultrasound treatment [2x 0.25 min]	34.40	32.93	1.47	24.30	20.05	4.25	3490	32.68	2.22	12.00	6.52	5.48
03.03.2008	38	ultrasound treatment [2x 0.25 min]	36.40	34.90	1.50	27.10	22.98	4.12	37,70	31.67	6.03	20.50	20.50	0.00
04.03.2008	39	ultrasound treatment [2x 0.25 min]	35.20	34.09	1.11	18.80	14.58	4.22	38,60	38.04	0.56	7.79	3.43	4.36
05.03.2008	40	ultrasound treatment [2x 0.25 min]	32.50	31.96	0.54	23.00	19.67	3.33	32,20	31.61	0.59	12.80	6.97	5.83
06.03.2008	41	ultrasound treatment [2x 0.25 min]	35.70	35.19	0.51	22.20	19.55	2.65	37,90	34.06	3.84	23.10	16.37	6.73
07.03.2008	42	ultrasound treatment [2x 0.25 min]	31.10	30.63	0.47	20.70	18.53	2.17	34.60	34.21	0.39	19.00	13.19	5.81
08.03.2008	43	ultrasound treatment [2x 0.25 min]	34.50	33.85	0.65	22.70	20.71	1.99	42.80	42.11	0.69	11.90	6.74	5.16
09.03.2008	44	ultrasound treatment [2x 0.25 min]	35.90	35.13	0.77	23.10	20.76	2.34	43.10	41.87	1.23	14.50	7.60	6.90
10.03.2008	45	ultrasound treatment [2x 0.25 min]	37.70	35.77	1.93	24.00	21.12	2.88	41.30	37.13	4.17	17.20	8.30	8.90
11.03.2008	46	ultrasound treatment [2x 0.25 min]	33.80	32.80	1.00	17.30	13.85	3.45	38.40	36.67	1.73	8.20	3.89	4.31
12.03.2008	47	ultrasound treatment [2x 0.25 min]	30.90	30.26	0.64	18.80	15.79	3.01	37.00	34.77	2.23	12.20	6.36	5.84
13.03.2008	48	ultrasound treatment [2x 0.25 min]	26.70	25.69	1.01	14.60	11.98	2.62	37.40	35.94	1.46	13.50	7.01	6.49
14.03.2008	49	ultrasound treatment [2x 0.25 min]	31.80	30.75	1.05	19.00	15.82	3.18	32.10	31.66	0.44	12.50	7.42	5.08
15.03.2008	50	ultrasound treatment [2x 0.25 min]	28.60	27.67	0.93	16.60	14.08	2.52	38.40	37.52	0.88	15.50	9.77	5.73
16.03.2008	51	ultrasound treatment [2x 0.25 min]	38.80	37.75	1.05	23.10	16.81	6.29	35.70	35.24	0.46	13.70	10.48	3.22
17.03.2008	52	ultrasound treatment [2x 0.25 min]	32.10	30.91	1.19	18.00	14.17	3.83	35.70	32.22	3.48	17.10	9.79	7.31

18.03.2008	53	ultrasound treatment [2x 0.25 min]	34.70	33.72	0.98	15.80	11.69	4.11	35.00	34.27	0.73	7.81	2.20	5.61
19.03.2008	54	ultrasound treatment [2x 0.25 min]	26.80	25.67	1.13	13.10	9.07	4.03	36.70	35.47	1.23	14.50	6.47	8.03
20.03.2008	55	ultrasound treatment [2x 0.25 min]	28.70	27.16	1.54	14.10	9.95	4.15	30.70	28.99	1.71	10.60	3.83	6.77
21.03.2008	56	ultrasound treatment [2x 0.25 min]	34.40	33.46	0.94	21.40	16.46	4.94	31.70	29.76	1.94	13.40	6.12	7.28
22.03.2008	57	ultrasound treatment [2x 0.25 min]	30.40	29.05	1.35	17.00	12.43	4.57	30.50	28.57	1.93	4.67	0.35	4.32
23.03.2008	58	ultrasound treatment [2x 0.25 min]	32.90	30.53	2.37	20.50	15.43	5.07	27.90	26.07	1.83	16.10	10.75	5.35
24.03.2008	59	ultrasound treatment [2x 0.25 min]	31.30	28.67	2.63	12.20	6.75	5.45	31.30	28.94	2.36	14.50	10.07	4.43
25.03.2008	60	ultrasound treatment [2x 0.25 min]	31.20	30.56	0.64	17.70	13.27	4.43	33.10	31.55	1.55	9.51	4.74	4.77
26.03.2008	61	ultrasound treatment [2x 0.25 min]	32.30	31.67	0.63	18.00	13.97	4.03	33.50	31.58	1.92	13.50	7.64	5.86
27.03.2008	62	ultrasound treatment [2x 0.25 min]	28.70	27.99	0.71	16.30	12.20	4.10	31.00	29.07	1.93	13.30	8.90	4.40
28.03.2008	63	ultrasound treatment [2x 0.25 min]	28.70	27.87	0.83	17.80	13.27	4.53	34.40	33.66	0.74	18.80	15.02	3.78
29.03.2008	64	ultrasound treatment [2x 0.25 min]	27.20	26.42	0.79	17.00	14.10	2.90	27.80	26.82	0.99	13.80	10.06	3.74
30.03.2008	65	ultrasound treatment [2x 0.25 min]	25.80	25.18	0.62	14.90	12.23	2.67	30.20	27.92	2.28	16.90	12.63	4.27
31.03.2008	66	ultrasound treatment [2x 0.25 min]	25.90	24.99	0.91	15.10	12.22	2.88	29.20	28.04	1.16	18.60	15.54	3.06
01.04.2008	67	ultrasound treatment [2x 0.25 min]	31.30	30.01	1.29	15.50	11.10	4.40	35.00	34.02	0.98	19.70	15.84	3.86
02.04.2008	68	ultrasound treatment [2x 1 min]	32.60	32.30	0.30	18.40	15.47	2.93	33.60	31.03	2.57	16.30	11.88	4.42
03.04.2008	69	ultrasound treatment [2x 1 min]	32.80	31.64	1.16	20.40	17.03	3.37	39.70	38.32	1.38	22.60	18.13	4.47
04.04.2008	70	ultrasound treatment [2x 1 min]	31.40	30.48	0.92	19.70	16.13	3.57	32.00	31.21	0.79	17.10	12.95	4.15
05.04.2008	71	ultrasound treatment [2x 1 min]	35.20	33.95	1.25	23.40	19.40	4.00	39.10	37.04	2.06	18.00	13.40	4.60
06.04.2008	72	ultrasound treatment [2x 1 min]	37.70	37.03	0.67	23.40	19.20	4.20	34.40	33.79	0.61	22.20	19.38	2.82
07.04.2008	73	ultrasound treatment [2x 1 min]	33.20	32.33	0.87	20.60	16.52	4.08	31.50	30.66	0.84	12.90	9.36	3.54
08.04.2008	74	ultrasound treatment [2x 1 min]	36.30	35.48	0.82	21.50	17.51	3.99	37.50	35.87	1.63	11.40	6.44	4.96
09.04.2008	75	ultrasound treatment [2x 1 min]	39.80	39.64	0.16	26.40	23.19	3.21	34.10	33.62	0.48	9.96	5.59	4.37
10.04.2008	76	ultrasound treatment [2x 1 min]	31.20	30.97	0.23	18.00	14.96	3.04	36.40	35.67	0.73	12.20	6.57	5.63
11.04.2008	77	ultrasound treatment [2x 1 min]	32.40	31.96	0.44	19.80	16.74	3.06	31.10	29.91	1.19	11.20	6.63	4.57
12.04.2008	78	ultrasound treatment [2x 1 min]	28.10	26.88	1.22	18.00	14.91	3.09	30.80	28.64	2.16	16.30	11.04	5.26
13.04.2008	79	ultrasound treatment [2x 1 min]	24.90	21.82	3.08	14.50	11.41	3.09	26.90	23.44	3.46	3.23	-1.10	4.33
14.04.2008	80	ultrasound treatment [2x 1 min]	16.30	12.68	3.62	4.95	3.32	1.63	13.50	8.41	5.09	1.87	0.58	1.29
15.04.2008	81	ultrasound treatment [2x 1 min]	12.30	6.88	5.42	0.00	-0.11	0.11	17.20	12.70	4.50	4.33	1.56	2.77

16.04.2008	82	ultrasound treatment [2x 1 min]	37.10	35.32	1.78	23.70	20.87	2.83	35.40	31.99	3.41	14.90	10.65	4.25
17.04.2008	83	ultrasound treatment [2x 1 min]	38.50	38.41	0.09	20.40	17.21	3.19	44.00	42.33	1.67	5.31	4.16	1.15
18.04.2008	84	ultrasound treatment [2x 1 min]	39.20	39.20	0.00	23.30	19.60	3.70	38.40	38.40	0.00	18.70	14.20	4.50
19.04.2008	85	ultrasound treatment [2x 1 min]	35.00	34.71	0.29	20.00	17.14	2.86	38.40	37.47	0.93	21.50	16.72	4.78
20.04.2008	86	ultrasound treatment [2x 1 min]	35.20	34.88	0.32	18.30	15.63	2.67	40.20	39.09	1.11	22.90	17.58	5.32
21.04.2008	87	ultrasound treatment [2x 1 min]	35.20	34.91	0.29	18.20	15.37	2.83	40.00	38.27	1.73	23.70	17.01	6.69
22.04.2008	88	ultrasound treatment [2x 1 min]	31.80	31.52	0.28	13.30	11.52	1.78	39.80	39.05	0.75	15.90	8.54	7.36
23.04.2008	89	ultrasound treatment [2x 1 min]	39.10	38.82	0.28	24.50	21.69	2.81	31.60	30.59	1.01	9.52	2.23	7.29
24.04.2008	90	ultrasound treatment [2x 1 min]	41.50	40.96	0.54	23.10	20.04	3.06	23.00	21.25	1.75	3.91	0.26	3.65
25.04.2008	91	ultrasound treatment [2x 1 min]	45.80	45.08	0.72	27.00	23.17	3.83	30.00	29.15	0.85	8.10	2.29	5.81
26.04.2008	92	ultrasound treatment [2x 1 min]	40.40	39.52	0.88	20.70	16.53	4.17	32.50	30.84	1.66	12.30	4.27	8.03
27.04.2008	93	ultrasound treatment [2x 1 min]	36.40	34.82	1.58	18.80	14.68	4.12	39.40	36.34	3.06	18.90	9.70	9.20
28.04.2008	94	ultrasound treatment [2x 1 min]	34.30	32.84	1.46	16.10	13.13	2.97	40.90	36.44	4.46	22.90	12.30	10.60
29.04.2008	95	ultrasound treatment [2x 1 min]	36.50	35.63	0.87	18.50	14.83	3.67	35.80	34.19	1.61	14.40	7.19	7.21
30.04.2008	96	ultrasound treatment [2x 1 min]	31.50	29.46	2.04	15.50	11.82	3.68	38.20	36.09	2.11	14.80	4.30	10.50
01.05.2008	97	ultrasound treatment [2x 1 min]	37.70	35.56	2.14	21.50	16.22	5.28	34.10	30.12	3.98	12.80	3.99	8.81
02.05.2008	98	ultrasound treatment [2x 1 min]	34.10	31.94	2.16	21.20	16.44	4.76	31.00	27.67	3.33	11.10	2.91	8.19
03.05.2008	99	ultrasound treatment [2x 1 min]	34.10	33.38	0.72	19.90	16.55	3.35	37.80	34.73	3.07	16.40	7.19	9.21
04.05.2008	100	ultrasound treatment [2x 1 min]	33.70	32.22	1.48	19.50	16.20	3.30	32.70	29.44	3.26	18.00	8.97	9.03
05.05.2008	101	ultrasound treatment [2x 1 min]	31.50	29.38	2.12	15.80	12.72	3.08	35.80	32.30	3.50	23.30	12.90	10.40
06.05.2008	102	ultrasound treatment [2x 1 min]	31.60	29.82	1.78	13.30	10.36	2.94	34.10	31.71	2.39	8.25	2.48	5.77
07.05.2008	103	ultrasound treatment [2x 1 min]	33.20	31.84	1.36	14.40	11.35	3.05	33.90	29.69	4.21	8.08	2.05	6.03
08.05.2008	104	ultrasound treatment [2x 1 min]	33.60	32.57	1.03	16.20	12.90	3.30	38.20	35.72	2.48	1.06	0.35	0.71
09.05.2008	105	ultrasound treatment [2x 1 min]	31.60	30.76	0.84	13.30	10.46	2.84	33.70	32.13	1.57	0.00	0.00	0.00

Table 4.K Removal rates in testing and control reactor (experiment 4, Chapter 6)

			removal rates	(at 20° C)
date	day of the experiment	operational conditions	testing reactor	control reactor
			[g N d^{-1} m^{-2}]	[g N d^{-1} m^{-2}]
26.01.2008	1	no shear force	0.43	0.57
27.01.2008	2	no shear force	0,.47	0.39
28.01.2008	3	no shear force	0.43	0.39
29.01.2008	4	no shear force	0.72	0.47
30.01.2008	5	no shear force	0.51	0.38
31.01.2008	6	no shear force	0.64	0.39
01.02.2008	7	no shear force	0.37	0.24
02.02.2008	8	no shear force	0.61	0.47
03.02.2008	9	no shear force	0.65	0.23
04.02.2008	10	no shear force	0.56	0.23
05.02.2008	11	no shear force	0.56	0.54
06.02.2008	12	no shear force	0.81	0.70
07.02.2008	13	no shear force	0.46	0.37
08.02.2008	14	no shear force	0.63	0.50
09.02.2008	15	no shear force	0.54	0.66
10.02.2008	16	no shear force	0.54	0.57
11.02.2008	17	no shear force	0.57	0.73
12.02.2008	18	no shear force	1.60	1.65
13.02.2008	19	no shear force	0.64	0.63
14.02.2008	20	no shear force	0.61	1.04
15.02.2008	21	no shear force	0.56	1.01
16.02.2008	22	no shear force	0.47	0.69
17.02.2008	23	no shear force	0.46	0.64
18.02.2008	24	no shear force	0.47	0.63
19.02.2008	25	no shear force	0.73	0.81
20.02.2008	26	no shear force	0.62	0.72
21.02.2008	27	no shear force	0.33	0.86
22.02.2008	28	no shear force	0.25	0.35
23.02.2008	29	no shear force	0.61	0.51
24.02.2008	30	no shear force	0.63	0.48
25.02.2008	31	ultrasound treatment [2x 0.25 min]	0.39	0.53
26.02.2008	32	ultrasound treatment [2x 0.25 min]	0.81	0.49
27.02.2008	33	ultrasound treatment [2x 0.25 min]	0.57	0.62
28.02.2008	34	ultrasound treatment [2x 0.25 min]	0.85	0.27
29.02.2008	35	ultrasound treatment [2x 0.25 min]	0.54	0.69
01.03.2008	36	ultrasound treatment [2x 0.25 min]	0.51	0.73
02.03.2008	37	ultrasound treatment [2x 0.25 min]	0.52	0.63
03.03.2008	38	ultrasound treatment [2x 0.25 min]	0.46	0.48
04.03.2008	39	ultrasound treatment [2x 0.25 min]	0.83	0.86
05.03.2008	40	ultrasound treatment [2x 0.25 min]	0.47	0.53

06.03.2008	41	ultrasound treatment [2x 0.25 min]	0.68	0.43
07.03.2008	42	ultrasound treatment [2x 0.25 min]	0.52	0.45
08.03.2008	43	ultrasound treatment [2x 0.25 min]	0.67	0.90
09.03.2008	44	ultrasound treatment [2x 0.25 min]	0.70	0.78
10.03.2008	45	ultrasound treatment [2x 0.25 min]	0.72	0.68
11.03.2008	46	ultrasound treatment [2x 0.25 min]	0.88	0.82
12.03.2008	47	ultrasound treatment [2x 0.25 min]	0.64	0.67
13.03.2008	48	ultrasound treatment [2x 0.25 min]	0.58	0.63
14.03.2008	49	ultrasound treatment [2x 0.25 min]	0.61	0.52
15.03.2008	50	ultrasound treatment [2x 0.25 min]	0.63	0.60
16.03.2008	51	ultrasound treatment [2x 0.25 min]	0.78	0.61
17.03.2008	52	ultrasound treatment [2x 0.25 min]	0.69	0.51
18.03.2008	53	ultrasound treatment [2x 0.25 min]	0.91	0.74
19.03.2008	54	ultrasound treatment [2x 0.25 min]	0.63	0.61
20.03.2008	55	ultrasound treatment [2x 0.25 min]	0.64	0.55
21.03.2008	56	ultrasound treatment [2x 0.25 min]	0.59	0.52
22.03.2008	57	ultrasound treatment [2x 0.25 min]	0.62	0.70
23.03.2008	58	ultrasound treatment [2x 0.25 min]	0.57	0.21
24.03.2008	59	ultrasound treatment [2x 0.25 min]	1.17	0.55
25.03.2008	60	ultrasound treatment [2x 0.25 min]	0.73	0.71
26.03.2008	61	ultrasound treatment [2x 0.25 min]	0.65	0.55
27.03.2008	62	ultrasound treatment [2x 0.25 min]	0.55	0.47
28.03.2008	63	ultrasound treatment [2x 0.25 min]	0.49	0.42
29.03.2008	64	ultrasound treatment [2x 0.25 min]	0.48	0.37
30.03.2008	65	ultrasound treatment [2x 0.25 min]	0.49	0.34
31.03.2008	66	ultrasound treatment [2x 0.25 min]	0.52	0.27
01.04.2008	67	ultrasound treatment [2x 0.25 min]	0.77	0.42
02.04.2008	68	ultrasound treatment [2x 1 min]	0.77	0.46
03.04.2008	69	ultrasound treatment [2x 1 min]	0.67	0.48
04.04.2008	70	ultrasound treatment [2x 1 min]	0.64	0.42
05.04.2008	71	ultrasound treatment [2x 1 min]	0.66	0.57
06.04.2008	72	ultrasound treatment [2x 1 min]	0.79	0.34
07.04.2008	73	ultrasound treatment [2x 1 min]	0.65	0.50
08.04.2008	74	ultrasound treatment [2x 1 min]	0.76	0.69
09.04.2008	75	ultrasound treatment [2x 1 min]	0.81	0.63
10.04.2008	76	ultrasound treatment [2x 1 min]	0.74	0.64
11.04.2008	77	ultrasound treatment [2x 1 min]	0.70	0.52
12.04.2008	78	ultrasound treatment [2x 1 min]	0.57	0.39
13.04.2008	79	ultrasound treatment [2x 1 min]	0.61	0.66
14.04.2008	80	ultrasound treatment [2x 1 min]	0.56	0.32
15.04.2008	81	ultrasound treatment [2x 1 min]	0.74	0.40
16.04.2008	82	ultrasound treatment [2x 1 min]	0.79	0.54
17.04.2008	83	ultrasound treatment [2x 1 min]	1.09	0.29
18.04.2008	84	ultrasound treatment [2x 1 min]	0.81	0.38

19.04.2008	85	ultrasound treatment [2x 1 min]	0.73	0.37
20.04.2008	86	ultrasound treatment [2x 1 min]	0.81	0.40
21.04.2008	87	ultrasound treatment [2x 1 min]	0.81	0.37
22.04.2008	88	ultrasound treatment [2x 1 min]	0.81	0.54
23.04.2008	89	ultrasound treatment [2x 1 min]	0.68	0.51
24.04.2008	90	ultrasound treatment [2x 1 min]	0.83	0.43
25.04.2008	91	ultrasound treatment [2x 1 min]	0.87	0.77
26.04.2008	92	ultrasound treatment [2x 1 min]	0.71	0.35
27.04.2008	93	ultrasound treatment [2x 1 min]	0.83	0.49
28.04.2008	94	ultrasound treatment [2x 1 min]	0.80	0.42
29.04.2008	95	ultrasound treatment [2x 1 min]	0.78	0.50
30.04.2008	96	ultrasound treatment [2x 1 min]	0.75	0.54
01.05.2008	97	ultrasound treatment [2x 1 min]	0.75	0.49
02.05.2008	98	ultrasound treatment [2x 1 min]	0.60	0.43
03.05.2008	99	ultrasound treatment [2x 1 min]	0.68	0.50
04.05.2008	100	ultrasound treatment [2x 1 min]	0.67	0.31
05.05.2008	101	ultrasound treatment [2x 1 min]	0.80	0.28
06.05.2008	102	ultrasound treatment [2x 1 min]	0.88	0.63
07.05.2008	103	ultrasound treatment [2x 1 min]	0.86	0.59
08.05.2008	104	ultrasound treatment [2x 1 min]	0.89	0.50
09.05.2008	105	ultrasound treatment [2x 1 min]	0.98	0.79

Table 4.L pH, DO and temperature in influent wastewater (experiment 4, Chapter 6)

		influent testing reactor			influent control reactor		
Date	**Operational conditions**	**pH**	**temperature [°C]**	**DO [mg O_2 l^{-1}]**	**pH**	**temperature [°C]**	**DO [mg O_2 l^{-1}]**
26.01.2008	no shear force	7.16	18.90	0.10	7.11	18.80	0.10
27.01.2008	no shear force	7.06	19.30	0.10	7.09	19.10	0.10
28.01.2008	no shear force	7.03	18.40	0.10	7.07	18.70	0.50
29.01.2008	no shear force	7.08	17.70	2.80	7.16	18.00	2.20
30.01.2008	no shear force	7.08	16.20	3.10	7.05	16.60	2.50
31.01.2008	no shear force	7.08	15.80	3.10	7.30	15.80	2.30
01.02.2008	no shear force	7.01	17.30	2.60	6.96	17.70	1.60
02.02.2008	no shear force	7.20	19.10	1.80	7.10	18.80	1.70
03.02.2008	no shear force	6.98	17.80	2.60	7.03	17.90	1.70
04.02.2008	no shear force	7.08	17.80	1.80	7.02	18.00	0.70
05.02.2008	no shear force	7.16	17.50	1.80	7.05	17.80	1.80
06.02.2008	no shear force	7.20	18.20	1.40	7.31	17.10	0.80
07.02.2008	no shear force	7.37	18.60	4.30	6.96	18.40	2.50
08.02.2008	no shear force	7.00	18.50	3.20	7.27	18.40	0.40
09.02.2008	no shear force	7.11	19.00	2.70	6.98	18.90	1.60
10.02.2008	no shear force	7.18	18.70	3.00	7.35	17.40	2.00
11.02.2008	no shear force	7.09	15.20	0.10	6.91	15.70	0.70
12.02.2008	no shear force	7.01	16.00	1.80	7.16	15.80	0.20
13.02.2008	no shear force	7.03	16.60	4.50	6.93	16.70	3.10
14.02.2008	no shear force	7.02	15.70	3.60	7.20	15.50	1.50
15.02.2008	no shear force	7.07	15.40	4.10	6.93	15.60	2.50
16.02.2008	no shear force	7.11	17.40	3.90	7.25	17.10	2.50
17.02.2008	no shear force	7.14	17.80	1.00	7.01	18.30	1.80
18.02.2008	no shear force	7.04	19.70	2.70	7.22	18.20	0.70
19.02.2008	no shear force	7.04	17.50	0.60	7.00	17.80	0.60
20.02.2008	no shear force	7.14	15.90	2.50	7.25	15.90	1.60

21.02.2008	no shear force	7.12	15.50	2.70	7.04	15.90	2.30
22.02.2008	no shear force	7.06	17.90	1.60	7.28	17.60	0.10
23.02.2008	no shear force	7.14	18.80	1.80	7.04	18.50	2.80
24.02.2008	no shear force	7.09	19.20	0.30	7.36	18.60	0.10
25.02.2008	ultrasound treatment [2x 0.25 min]	7.15	18.80	0.00	7.06	19.00	0.10
26.02.2008	ultrasound treatment [2x 0.25 min]	7.28	19.40	0.10	7.29	19.50	0.00
27.02.2008	ultrasound treatment [2x 0.25 min]	7.08	19.30	0.80	7.10	18.90	0.50
28.02.2008	ultrasound treatment [2x 0.25 min]	7.21	18.30	0.00	7.20	18.70	0.00
29.02.2008	ultrasound treatment [2x 0.25 min]	7.20	19.10	0.00	7.19	19.10	0.00
01.03.2008	ultrasound treatment [2x 0.25 min]	7.17	19.20	0.00	7.12	19.00	0.00
02.03.2008	ultrasound treatment [2x 0.25 min]	7.10	18.90	0.00	7.15	18.90	0.00
03.03.2008	ultrasound treatment [2x 0.25 min]	7.15	19.20	0.00	7.35	18.60	0.00
04.03.2008	ultrasound treatment [2x 0.25 min]	7.23	18.40	0.10	7.16	18.80	0.50
05.03.2008	ultrasound treatment [2x 0.25 min]	7.02	18.60	3.10	7.13	18.70	1.60
06.03.2008	ultrasound treatment [2x 0.25 min]	7.24	18.30	2.00	7.57	16.90	0.40
07.03.2008	ultrasound treatment [2x 0.25 min]	7.20	17.90	0.10	7.20	18.00	0.00
08.03.2008	ultrasound treatment [2x 0.25 min]	7.14	18.40	0.00	7.23	18.40	0.00
09.03.2008	ultrasound treatment [2x 0.25 min]	7.17	18.50	0.00	7.18	18.60	0.00
10.03.2008	ultrasound treatment [2x 0.25 min]	7.15	18.60	0.00	7.19	18.70	0.00
11.03.2008	ultrasound treatment [2x 0.25 min]	7.24	18.80	0.00	7.18	19.00	0.00
12.03.2008	ultrasound treatment [2x 0.25 min]	7.06	19.40	1.70	7.31	18.70	0.10
13.03.2008	ultrasound treatment [2x 0.25 min]	7.20	19.40	0.10	7.35	18.20	0.10
14.03.2008	ultrasound treatment [2x 0.25 min]	7.17	19.60	1.50	7.04	19.70	1.00
15.03.2008	ultrasound treatment [2x 0.25 min]	7.18	19.50	1.00	7.24	19.20	0.20
16.03.2008	ultrasound treatment [2x 0.25 min]	7.26	19.30	0.10	7.17	19.60	0.10
17.03.2008	ultrasound treatment [2x 0.25 min]	7.14	19.20	000	7.50	17.50	0.00
18.03.2008	ultrasound treatment [2x 0.25 min]	7.14	19.50	0.00	7.07	19.90	0.20

19.03.2008	ultrasound treatment [2x 0.25 min]	7.15	19.70	2.00	7.11	19.90	1.60
20.03.2008	ultrasound treatment [2x 0.25 min]	7.14	19.60	0.20	7.16	19.60	0.60
21.03.2008	ultrasound treatment [2x 0.25 min]	7.19	19.90	0.30	7.18	19.90	0.30
22.03.2008	ultrasound treatment [2x 0.25 min]	7.17	19.90	0.40	7.22	19.90	0.40
23.03.2008	ultrasound treatment [2x 0.25 min]	7.25	19.80	0.10	7.12	20.10	0.10
24.03.2008	ultrasound treatment [2x 0.25 min]	7.26	19.50	0.00	7.23	19.50	0.00
25.03.2008	ultrasound treatment [2x 0.25 min]	7.11	19.70	0.10	8.07	20.10	0.10
26.03.2008	ultrasound treatment [2x 0.25 min]	7.12	19.40	0.00	7.20	19.50	0.00
27.03.2008	ultrasound treatment [2x 0.25 min]	7.22	19.50	0.00	7.25	19.50	0.00
28.03.2008	ultrasound treatment [2x 0.25 min]	7.24	19.40	0.00	7.20	19.80	0.00
29.03.2008	ultrasound treatment [2x 0.25 min]	7.26	19.70	1.00	7.14	20.00	0.50
30.03.2008	ultrasound treatment [2x 0.25 min]	7.22	19.80	0.00	7.29	20.00	0.00
31.03.2008	ultrasound treatment [2x 0.25 min]	7.24	20.20	0.00	7.19	20.40	0.00
01.04.2008	ultrasound treatment [2x 0.25 min]	7.15	19.60	0.00	7.13	20.20	0.00
02.04.2008	ultrasound treatment [2x 1 min]	7.22	19.70	0.00	7.37	19.90	0.00
03.04.2008	ultrasound treatment [2x 1 min]	7.25	20.40	0.10	7.31	19.80	0.10
04.04.2008	ultrasound treatment [2x 1 min]	7.28	19.60	0.10	7.19	20.50	0.10
05.04.2008	ultrasound treatment [2x 1 min]	7.21	19.70	0.00	7.29	19.90	0.00
06.04.2008	ultrasound treatment [2x 1 min]	7.15	19.90	0.00	7.13	20.40	0.00
07.04.2008	ultrasound treatment [2x 1 min]	7.25	20.00	0.00	7.20	20.30	0.00
08.04.2008	ultrasound treatment [2x 1 min]	7.26	20.30	0.00	7.27	20.10	0.00
09.04.2008	ultrasound treatment [2x 1 min]	7.21	21.00	0.00	7.09	20.60	0.20
10.04.2008	ultrasound treatment [2x 1 min]	7.27	20.90	0.20	7.26	20.40	0.00
11.04.2008	ultrasound treatment [2x 1 min]	7.15	20.40	0.00	7.22	20.50	0.00
12.04.2008	ultrasound treatment [2x 1 min]	7.22	20.20	0.10	7.22	20.20	0.10
13.04.2008	ultrasound treatment [2x 1 min]	7.33	20.90	0.10	7.37	20.30	0.10
14.04.2008	ultrasound treatment [2x 1 min]	7.22	20.10	000	7.78	20.40	0.00

15.04.2008	ultrasound treatment [2x 1 min]	8.50	20.00	0.10	8.21	19.50	0.00
16.04.2008	ultrasound treatment [2x 1 min]	7.35	21.60	0.00	7.58	21.40	0.00
17.04.2008	ultrasound treatment [2x 1 min]	6.87	22.20	0.00	7.57	20.90	0.00
18.04.2008	ultrasound treatment [2x 1 min]	7.16	21.00	0.00	7.16	21.10	0.00
19.04.2008	ultrasound treatment [2x 1 min]	7.19	21.10	0.00	7.21	21.30	0.00
20.04.2008	ultrasound treatment [2x 1 min]	7.30	21.40	0.00	7.36	21.40	0.00
21.04.2008	ultrasound treatment [2x 1 min]	7.35	22.10	0.00	7.60	22.00	0.00
22.04.2008	ultrasound treatment [2x 1 min]	7.28	21.30	0.00	7.23	22.30	0.00
23.04.2008	ultrasound treatment [2x 1 min]	7.23	21.00	0.00	7.28	21.20	0.10
24.04.2008	ultrasound treatment [2x 1 min]	7.40	21.00	0.10	7.44	21.00	0.10
25.04.2008	ultrasound treatment [2x 1 min]	7.43	20.60	0.20	7.20	21.20	0.20
26.04.2008	ultrasound treatment [2x 1 min]	7.32	19.30	0.30	7.29	19.50	0.30
27.04.2008	ultrasound treatment [2x 1 min]	7.33	20.70	0.30	7.30	20.70	0.30
28.04.2008	ultrasound treatment [2x 1 min]	7.29	20.80	0.10	7.35	20.70	0.10
29.04.2008	ultrasound treatment [2x 1 min]	7.27	20.70	0.10	7.24	20.80	0.10
30.04.2008	ultrasound treatment [2x 1 min]	7.30	20.80	0.20	7.29	20.90	0.30
01.05.2008	ultrasound treatment [2x 1 min]	7.31	20.70	0.20	7.31	20.80	0.20
02.05.2008	ultrasound treatment [2x 1 min]	7.33	20.60	0.20	7.21	21.00	0.20
03.05.2008	ultrasound treatment [2x 1 min]	7.32	20.60	0.10	7.18	20.90	0.10
04.05.2008	ultrasound treatment [2x 1 min]	7.18	20.80	0.10	7.21	20.90	0.10
05.05.2008	ultrasound treatment [2x 1 min]	7.29	20.80	0.20	7.25	21.00	0.20
06.05.2008	ultrasound treatment [2x 1 min]	7.28	20.50	0.10	7.18	20.80	0.10
07.05.2008	ultrasound treatment [2x 1 min]	7.33	20.50	0.20	7.43	20.70	0.20
08.05.2008	ultrasound treatment [2x 1 min]	7.27	20.60	0.10	7.32	20.90	0.10
09.05.2008	ultrasound treatment [2x 1 min]	0.00	0.00	0.00	0.00	0.00	0.00

Table 4.M pH, DO and temperature in influent wastewater (experiment 4, Chapter 6)

		testing reactor			control reactor		
Date	Operational conditions	pH	temperature [°C]	DO [mg O_2 l^{-1}]	pH	temperature [°C]	DO [mg O_2 l^{-1}]
26.01.2008	no shear force	7.90	19.00	0.00	8.53	19.40	0.00
27.01.2008	no shear force	7.84	20.10	0.10	8.12	19.70	0.10
28.01.2008	no shear force	7.86	19.00	0.10	8.06	19.10	0.10
29.01.2008	no shear force	8.39	18.10	0.20	8.58	19.10	0.10
30.01.2008	no shear force	8.29	18.60	0.10	8.33	17.50	0.10
31.01.2008	no shear force	8.36	16.60	0.10	8.35	16.80	0.10
01.02.2008	no shear force	8.17	17.80	0.10	7.86	17.90	0.10
02.02.2008	no shear force	8.28	19.50	0.10	8.12	20.30	0.10
03.02.2008	no shear force	8.13	18.70	0.10	7.72	18.90	0.10
04.02.2008	no shear force	8.1	18.80	0.10	7.76	19.00	0.10
05.02.2008	no shear force	8.16	18.90	0.10	8.31	19.00	0.10
06.02.2008	no shear force	8.23	18.50	0.10	8.43	18.30	0.10
07.02.2008	no shear force	8.13	19.30	0.20	7.92	19.00	0.10
08.02.2008	no shear force	7.83	19.70	0.10	8.07	19.60	0.10
09.02.2008	no shear force	7.82	19.30	0.10	8.63	19.50	0.10
10.02.2008	no shear force	7.92	18.70	0.10	8.77	19.00	0.10
11.02.2008	no shear force	7.84	16.10	0.10	8.58	16.10	0.10
12.02.2008	no shear force	8.18	16.60	0.10	9.00	19.60	0.10
13.02.2008	no shear force	8.12	17.30	0.10	8.53	17.80	0.10
14.02.2008	no shear force	8.09	16.70	0.10	9.07	16.50	0.10
15.02.2008	no shear force	8.03	16.10	0.10	8.75	16.10	0.10
16.02.2008	no shear force	8.05	17.70	0.40	8.79	17.80	0.10
17.02.2008	no shear force	8.02	18.40	0.10	8.67	18.50	0.10
18.02.2008	no shear force	7.9	19.00	0.20	8.78	19.20	0.10
19.02.2008	no shear force	8.28	18.20	0.10	8.88	19.50	0.00
20.02.2008	no shear force	8.3	16.60	0.10	9.02	17.40	0.00

21.02.2008	no shear force	8.16	16.60	0.10	8.86	16.40	0.10
22.02.2008	no shear force	8.05	19.60	0.10	8.63	19.20	0.10
23.02.2008	no shear force	8.13	19.50	0.10	8.47	19.20	0.00
24.02.2008	no shear force	8.13	19.80	0.00	8.57	19.90	0.00
25.02.2008	ultrasound treatment [2x 0.25 min]	7.96	19.80	0.00	844	19.90	0.00
26.02.2008	ultrasound treatment [2x 0.25 min]	8.41	21.40	0.00	8,82	20.90	0.00
27.02.2008	ultrasound treatment [2x 0.25 min]	8.14	19.90	0.10	8.79	19.90	0.00
28.02.2008	ultrasound treatment [2x 0.25 min]	8.24	19.20	0.00	8.83	19.70	0.00
29.02.2008	ultrasound treatment [2x 0.25 min]	8.17	20.10	0.00	8.82	20.30	0.00
01.03.2008	ultrasound treatment [2x 0.25 min]	8.13	20.30	0.00	8.65	19.20	0.00
02.03.2008	ultrasound treatment [2x 0.25 min]	7.93	19.40	0.00	8.56	19.40	0.00
03.03.2008	ultrasound treatment [2x 0.25 min]	7.98	21.00	0.00	8.54	20,70	0.00
04.03.2008	ultrasound treatment [2x 0.25 min]	8.35	19.20	0.10	8.73	20,00	0.10
05.03.2008	ultrasound treatment [2x 0.25 min]	8.02	20.10	0.10	8.58	19.90	0.10
06.03.2008	ultrasound treatment [2x 0.25 min]	8.34	19.80	0.00	8.48	19.90	0.50
07.03.2008	ultrasound treatment [2x 0.25 min]	8.17	19.20	0.00	8.51	19.20	0.00
08.03.2008	ultrasound treatment [2x 0.25 min]	8.44	19.10	0.00	8.90	19.10	0.00
09.03.2008	ultrasound treatment [2x 0.25 min]	8.4	19.50	0.00	8.83	19.20	0.00
10.03.2008	ultrasound treatment [2x 0.25 min]	8.21	19.80	0.00	8.74	19.40	0.00
11.03.2008	ultrasound treatment [2x 0.25 min]	8.41	19.90	0.00	8.90	19.80	0,00
12.03.2008	ultrasound treatment [2x 0.25 min]	8.22	19.80	0.00	8.87	19.90	0.00
13.03.2008	ultrasound treatment [2x 0.25 min]	8.34	20.40	0.00	8.81	20.30	0.00
14.03.2008	ultrasound treatment [2x 0.25 min]	8.34	20.70	0.00	8.56	21.00	0.00
15.03.2008	ultrasound treatment [2x 0.25 min]	8.35	20.80	0.00	8.63	20.30	0.00
16.03.2008	ultrasound treatment [2x 0.25 min]	8.43	20.50	0.00	8.63	20.30	0.00
17.03.2008	ultrasound treatment [2x 0.25 min]	8.3	20.40	0.00	8.64	20.30	0.00
18.03.2008	ultrasound treatment [2x 0.25 min]	8.49	20.50	0.00	8.81	21.10	0.00

19.03.2008	ultrasound treatment [2x 0.25 min]	8.42	21.10	0.00	8.81	21.00	0.00
20.03.2008	ultrasound treatment [2x 0.25 min]	8.38	21.00	0.00	8.74	20.90	0.00
21.03.2008	ultrasound treatment [2x 0.25 min]	8.31	21.10	0.00	8.67	20.80	0.00
22.03.2008	ultrasound treatment [2x 0.25 min]	8.34	21.10	0.00	8.82	21.00	0.00
23.03.2008	ultrasound treatment [2x 0.25 min]	8.34	21.00	0.00	8.55	21.00	0.00
24.03.2008	ultrasound treatment [2x 0.25 min]	8.53	20.00	0.00	8.66	20.60	0.00
25.03.2008	ultrasound treatment [2x 0.25 min]	8.39	21.00	0.10	8.83	21.50	0.00
26.03.2008	ultrasound treatment [2x 0.25 min]	8.3	20.30	0.00	8.79	20.40	0.00
27.03.2008	ultrasound treatment [2x 0.25 min]	8.32	20.80	0.00	8.71	20.90	0.00
28.03.2008	ultrasound treatment [2x 0.25 min]	8.32	20.50	0.00	8.57	20.20	0.00
29.03.2008	ultrasound treatment [2x 0.25 min]	8.33	20.50	0.00	8.59	20.70	0.00
30.03.2008	ultrasound treatment [2x 0.25 min]	8.36	20.70	0.00	8.56	21.30	0.00
31.03.2008	ultrasound treatment [2x 0.25 min]	8.31	21.60	0.00	8.43	21.40	0.00
01.04.2008	ultrasound treatment [2x 0.25 min]	8.42	21.10	0.00	8.48	21.00	0.00
02.04.2008	ultrasound treatment [2x 1 min]	8.46	20.70	0.00	8.63	21.00	0.00
03.04.2008	ultrasound treatment [2x 1 min]	8.47	20.70	0.00	8.74	20.80	0.00
04.04.2008	ultrasound treatment [2x 1 min]	8.43	21.10	0.00	8.68	20.60	0.00
05.04.2008	ultrasound treatment [2x 1 min]	8.43	20.30	0.00	8.86	21.40	0.00
06.04.2008	ultrasound treatment [2x 1 min]	8.4	21.20	0.00	8.43	21.40	0.00
07.04.2008	ultrasound treatment [2x 1 min]	8.48	21.30	0.00	8.87	21.30	0.00
08.04.2008	ultrasound treatment [2x 1 min]	8.72	21.20	0.00	9.03	21.60	0.00
09.04.2008	ultrasound treatment [2x 1 min]	8.27	21.10	0.00	8.91	21.20	0.00
10.04.2008	ultrasound treatment [2x 1 min]	8.38	21.30	0.00	8.98	21.20	0.00
11.04.2008	ultrasound treatment [2x 1 min]	8.29	20.80	0.00	8.84	21.20	0.00
12.04.2008	ultrasound treatment [2x 1 min]	8.22	20.70	0.10	8.62	21.10	0.10
13.04.2008	ultrasound treatment [2x 1 min]	8.24	20.80	0.00	8.88	21.20	0.10
14.04.2008	ultrasound treatment [2x 1 min]	8.17	21.30	0.00	8.52	21.70	0.00

15.04.2008	ultrasound treatment [2x 1 min]	8.71	21.60	0.00	9.12	21.80	0.00
16.04.2008	ultrasound treatment [2x 1 min]	8.21	21.70	0.00	8.87	21.90	0.00
17.04.2008	ultrasound treatment [2x 1 min]	8.29	22.00	0.00	9.37	22.10	0.00
18.04.2008	ultrasound treatment [2x 1 min]	8.27	22.20	0.00	8.65	22.20	0.00
19.04.2008	ultrasound treatment [2x 1 min]	8.25	21.90	0.00	8.50	22.70	0.00
20.04.2008	ultrasound treatment [2x 1 min]	8.57	22.60	0.00	8.55	22.80	0.00
21.04.2008	ultrasound treatment [2x 1 min]	8.49	22.70	0.00	8.59	22.90	0.00
22.04.2008	ultrasound treatment [2x 1 min]	8.58	22.70	0.00	8.69	23.00	0.00
23.04.2008	ultrasound treatment [2x 1 min]	8.41	22.30	0.00	8.82	22.20	0.00
24.04.2008	ultrasound treatment [2x 1 min]	9.67	22.40	0.00	8.81	22.90	0.00
25.04.2008	ultrasound treatment [2x 1 min]	8.69	22.00	0.20	8.90	8.90	0.10
26.04.2008	ultrasound treatment [2x 1 min]	8.75	20.40	0.00	8.81	20.60	0.00
27.04.2008	ultrasound treatment [2x 1 min]	8.68	21.00	0.30	8.75	21.60	0.30
28.04.2008	ultrasound treatment [2x 1 min]	8.63	21.90	0.00	8.64	22.00	0.00
29.04.2008	ultrasound treatment [2x 1 min]	8.96	21.50	0.00	8.98	22.10	0.00
30.04.2008	ultrasound treatment [2x 1 min]	8.84	21.80	0.00	9.17	22.10	0.00
01.05.2008	ultrasound treatment [2x 1 min]	8.75	21.60	0.10	9.05	21.70	0.00
02.05.2008	ultrasound treatment [2x 1 min]	8.61	22.00	0.10	8.94	22.30	0.00
03.05.2008	ultrasound treatment [2x 1 min]	8.68	21.50	0.10	8.76	21.60	0.00
04.05.2008	ultrasound treatment [2x 1 min]	8.26	21.70	0.10	8.48	22.80	0.00
05.05.2008	ultrasound treatment [2x 1 min]	8.38	21.10	0.10	8.63	22.40	0.00
06.05.2008	ultrasound treatment [2x 1 min]	8.72	20.90	0.00	8.85	21.30	0.00
07.05.2008	ultrasound treatment [2x 1 min]	8.63	20.80	0.10	8.91	22.00	0.10
08.05.2008	ultrasound treatment [2x 1 min]	8.51	21.60	0.00	9.03	22.40	-0.60
09.05.2008	ultrasound treatment [2x 1 min]	8.5	21.60	0.00	8.45	21.20	0.00

Table 4.N TSS and VSS concentrations in influent from testing reactor (experiment 4, Chapter 6)

		influent		Effluent	
Date	day of the experiment	TSS	VSS	TSS	VSS
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
26.01.2008	1	1.88	25.98	36.43	23.75
27.01.2008	2	14.36	13.86	11.49	10.34
28.01.2008	3	6.92	5.11	27.00	24.50
29.01.2008	4	9.46	6.47	4.81	5.17
30.01.2008	5	6.28	5.29	7.62	5.96
31.01.2008	6	10.50	4.50	51.20	34.79
01.02.2008	7	3.23	2.43	30.87	22.40
02.02.2008	8	4.64	1.66	17.00	7.50
03.02.2008	9	4.50	7.50	8.50	8.50
04.02.2008	10	8.00	6.00	11.50	7.50
05.02.2008	11	11.03	10.52	10.00	7.50
06.02.2008	12	13.58	5.37	20.13	13.86
07.02.2008	13	3.69	1.06	19.50	13.50
08.02.2008	14	7.76	4.64	63.50	51.50
09.02.2008	15	56.93	35.64	85.31	73.41
10.02.2008	16	9.53	3.85	16.50	10.00
11.02.2008	17	5.97	3.97	24.50	17.50
12.02.2008	18	13.00	11.00	16.00	13.00
13.02.2008	19	6.68	5.45	7.48	6.22
14.02.2008	20	5.67	0.67	8.33	5.33
15.02.2008	21	2.00	8.50	6.97	11.,94
16.02.2008	22	-	-	-	-
17.02.2008	23	-	-	-	-
18.02.2008	24	10.00	9.00	14.00	12.00
19.02.2008	25	3.33	3.33	6.00	6.00
20.02.2008	26	6.30	4.33	6.80	5.20
21.02.2008	27	8.46	4.62	10.34	5.36
22.02.2008	28	12.00	10.50	24.00	20.00
23.02.2008	29	71.84	58.25	27.84	24.86
24.02.2008	30	29.00	25.00	40.32	33.87
25.02.2008	31	1.88	2.35	3.38	3.01
26.02.2008	32	5.49	0.00	5.95	4.76
27.02.2008	33	3.57	2.38	0.80	-1.60
28.02.2008	34	5.50	4.50	3.00	2.00
29.02.2008	35	2.50	1.50	3.70	2.47
01.03.2008	36	1.17	0.58	3.67	3.33
02.03.2008	37	0.89	1.79	3.50	3.50
03.03.2008	38	4.15	3.11	6.97	5.97
04.03.2008	39	2.00	2.00	4.50	3.50

05.03.2008	40	7.24	5.26	9.00	6.00
06.03.2008	41	4.00	1.50	5.00	2.50
07.03.2008	42	-1.50	-1.00	2.49	1.49
08.03.2008	43	0.72	1.45	6.47	4.98
09.03.2008	44	3.09	3.61	8.50	8.00
10.03.2008	45	3.39	1.69	8.42	7.43
11.03.2008	46	5.00	3.00	11.00	9.50
12.03.2008	47	5.00	4.50	6.47	6.47
13.03.2008	48	6.57	6.06	4.50	5.50
14.03.2008	49	7.50	4.50	6.00	3.50
15.03.2008	50	8.50	5.50	8.00	5.00
16.03.2008	51	9.00	5.50	9.45	6.97
17.03.2008	52	4.50	3.50	7.46	6.47
18.03.2008	53	2.49	5.47	5.00	6.00
19.03.2008	54	7.50	4.50	6.00	3.50
20.03.2008	55	11.54	6.59	7.00	4.00
21.03.2008	56	6.00	4.00	6.00	4.50
22.03.2008	57	3,.00	3.00	4.01	3.01
23.03.2008	58	5.00	3.50	6.95	6.95
24.03.2008	59	6.34	7.75	6.43	5.71
25.03.2008	60	1.50	1.00	6.50	5.00
26.03.2008	61	9.00	4.50	5.50	3.50
27.03.2008	62	5.08	3.55	5.50	4.50
28.03.2008	63	3.00	1.00	4.50	2.50
29.03.2008	64	2.00	1.50	5.50	4.50
30.03.2008	65	5.00	3.00	5.50	4.50
31.03.2008	66	5.50	2.50	5.99	3.49
01.04.2008	67	3.00	2.50	3.50	2.50
02.04.2008	68	5.00	3.00	5.00	1.50
03.04.2008	69	4.00	3.50	6.97	5.97
04.04.2008	70	1.50	0.00	1.50	1.50
05.04.2008	71	29.00	19.00	5.50	4.50
06.04.2008	72	1.00	2.49	5.47	4.98
07.04.2008	73	10.00	6.67	2.50	3.00
08.04.2008	74	2.94	0.74	3.50	2.00
09.04.2008	75	17.00	8.00	5.50	2.00
10.04.2008	76	4.17	3.33	4.50	2.50
11.04.2008	77	3.00	1.00	8.46	4.48
12.04.2008	78	15.03	9.33	9.50	6.50
13.04.2008	79	27.45	17.65	23.00	18.00
14.04.2008	80	31.37	27.45	22.81	19.30
15.04.2008	81	16.28	12.40	21.50	15.50
16.04.2008	82	39.34	29.51	15.84	14.85
17.04.2008	83	16.00	8.00	7.50	5.50

18.04.2008	84	1.50	0.00	5.50	4.00
19.04.2008	85	1.00	0.00	7.50	4.00
20.04.2008	86	2.70	3.78	8.50	8.00
21.04.2008	87	8.00	4.50	7.50	5.00
22.04.2008	88	22.00	3.50	8.00	4.00
23.04.2008	89	4.52	3.02	7.50	4.00
24.04.2008	90	6.00	4.00	19.50	13..00
25.04.2008	91	3.00	2.50	9.00	6.50
26.04.2008	92	1.50	1.50	8.50	5.00
27.04.2008	93	3.48	2.99	9.00	8.00
28.04.2008	94	2.50	3.00	11.50	9.50
29.04.2008	95	4.48	2.49	8.00	5.00
30.04.2008	96	3.50	2.00	11.00	7.00
01.05.2008	97	3.96	2.48	12.50	8.50
02.05.2008	98	1.02	0.00	7.50	5.50
03.05.2008	99	1.50	1.00	9.52	7.02
04.05.2008	100	4.00	2.50	13.50	10.50
06.05.2008	102	3.33	2.00	19.50	13.00
07.05.2008	103	8.70	3.73	12.50	6.50
08.05.2008	104	4.50	4.50	7.50	6.00
09.05.2008	105	1.52	-	5.47	-

Table 4.O TCOD and SCOD concentrations in influent from testing reactor (experiment 4, Chapter 6)

		influent		Effluent	
Date	day of the experiment	TCOD	SCOD	TCOD	SCOD
		mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
14.01.2008	20	51.67	30.67	44.67	40.33
15.01.2008	21	46.67	46.00	84.33	56.67
18.01.2008	24	45.67	41.67	52.67	49.33
28.02.2008	34	63.33	54.00	109.67	59.00
29.02.2008	35	69.00	65.00	85.00	65.33
1.03.2008	36	74.00	73.67	69.67	73.00
4.03.2008	39	78.33	65.00	72.00	65.33
5.03.2008	40	67.00	82.33	84.33	71.33
08.03.2008	43	105.67	73.00	97.00	74.67
09.03.2008	40	-	72.00	81.00	74.67
11.03.2008	46	81.67	57.67	45.00	85.67
15.03.2008	50	88.00	65.00	79.33	84.00
16.03.2008	51	85.33	75.00	69.67	64.67
22.03.2008	57	65.67	60.67	61.33	59.67
23.03.2008	58	57.67	63.33	60.67	63.67
30.03.2008	65	63.00	60.00	64.33	69.67
05.04.2008	71	54.00	52.67	57.67	46.00
06.04.2008	72	55.33	59.67	52.33	51.00
07.04.2008	73	54.00	49.67	62.33	53.33
08.04.2008	74	54.33	68.33	77.00	61.33
14.04.2008	80	101.67	71.33	91.67	71.00
19.04.2008	85	63.67	70.67	62.67	65.67
20.04.2008	86	63.33	58.00	61.00	69.67
26.04.2007	87	62.67	55.00	48.00	56.33
27.04.2008	93	49.33	51.00	59.33	58.67
1.05.2008	97	28.00	28.00	35.67	39.33
3.05.2008	99	43.00	41.67	29.67	45.00
4.05.2008	100	49.33	48.00	67.00	50.00
5.05.2008	101	52.33	48.33	-	-

Table 4.P Thickness, density (TS and VS) as well as VS/TS ratio in biofilm from testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	Average biofilm thickness [µm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS
28.01.2008	3	147	137	103	0.76
		317	84	52	0.62
	average	**232**	**110**	**78**	**0.69**
	st.dev	**120**	**37**	**36**	**0.10**
04.02.2008	10	96	90	47	0.52
		431	87	43	0.50
	average	**263**	**88**	**45**	**0.51**
	st.dev	**237**	**2**	**2**	**0.01**
11.02.2008	17	566	77	45	0.58
		386	113	63	0.56
	average	**476**	**95**	**54**	**0.57**
	st.dev	**127**	**26**	**13**	**0.01**
18.02.2008	24	224	124	59	0.47
		890	66	47	0.71
	average	**557**	**95**	**53**	**0.59**
	st.dev	**471**	**41**	**8**	**0.17**
25.02.2008	31	417	80	50	0.63
		624	108	83	0.77
	average	**521**	**94**	**66**	**0.70**
	st.dev	**146**	**19**	**23**	**0.10**
03.03.2008	38	823	102	58	0.58
		487	75	51	0.68
		21	170	100	0.59
		565	87	55	0.63
	average	**474**	**109**	**66**	**0.62**
	st.dev	**334**	**42**	**23**	**0.05**
10.03.2008	45	373	110	57	0.52
		172	260	180	0.69
		343	127	67	0.53
		129	160	87	0.54
	average	**254**	**164**	**97**	**0.57**
	st.dev	**121**	**67**	**56**	**0.08**
17.03.2008	52	584	66	46	0.70
		674	81	49	0.60
		351	88	48	0.55
		1324	72	42	0.59
	average	**733**	**77**	**46**	**0.61**
	st.dev	**417**	**10**	**3**	**0.06**
24.03.2008	59	536	68	53	0.78
		312	55	45	0.82
		711	118	68	0.58

		499	74	46	0.62
	average	**514**	**79**	**53**	**0.70**
	st.dev	**164**	**27**	**11**	**0.12**
31.03.2008	66	448	77	44	0.56
		882	43	30	0.70
		448	82	50	0.61
		405	60	38	0.63
	average	**546**	**66**	**40**	**0.62**
	st.dev	**225**	**18**	**9**	**0.06**
7.04.2008	73	533	85	53	0.62
		674	48	38	0.79
		293	115	80	0.70
		449	52	33	0.62
	average	**487**	**75**	**51**	**0.68**
	st.dev	**159**	**31**	**21**	**0.08**
14.04.2008	80	552	53	40	0.76
		778	74	54	0.73
		501	60	40	0.67
		246	133	70	0.53
	average	**519**	**80**	**51**	**0.67**
	st.dev	**218**	**36**	**14**	**0.10**
21.04.2008	87	688	68	48	0.71
		601	59	36	0.61
		629	54	37	0.67
		280	87	70	0.80
	average	**688**	**67**	**48**	**0.71**
	st.dev	**183**	**15**	**16**	**0.08**
28.04.2008	94	391	126	71	0.57
		526	62	44	0.71
		588	104	58	0.56
		671	94	58	0.62
	average	**544**	**96**	**58**	**0.61**
	st.dev	**118**	**26**	**11**	**0.07**
05.05.2008	101	1076	50	36	0.73
		624	87	73	0.83
		482	73	40	0.55
		223	100	60	0.60
	average	**601**	**78**	**52**	**0.68**
	st.dev	**357**	**22**	**17**	**0.13**

Table 4.Q Thickness, density (TS and VS) as well as VS/TS ratio in biofilm from control reactor (experiment 4, Chapter 6)

Date	Day of the experiment	Average biofilm thickness [µm]	TS [g l^{-1}]	VS [g l^{-1}]	VS/TS
28.01.2008	3	1034	69	37	0.53
		15	122	62	0.51
	average	**524**	**95**	**49**	**0.52**
	st.dev	**720**	**37**	**18**	**0.02**
04.02.2008	10	509	46	29	0.63
		683	79	36	0.45
	average	**596**	**62**	**32**	**0.54**
	st.dev	**123**	**24**	**5**	**0.12**
11.02.2008	17	799	69	34	0.50
		1752	51	30	0.58
	average	**1275**	**60**	**32**	**0.54**
	st.dev	**674**	**13**	**3**	**0.06**
18.02.2008	24	1068	53	34	0.64
		629	56	42	0.76
	average	**849**	**54**	**38**	**0.70**
	st.dev	**310**	**2**	**6**	**0.09**
25.02.2008	31	215	83	49	0.59
		155	95	73	0.76
	average	**185**	**89**	**61**	**0.68**
	st.dev	**43**	**9**	**17**	**0.12**
03.03.2008	38	471	78	43	0.55
		508	71	47	0.67
	average	**489**	**74**	**45**	**0.61**
	st.dev	**26**	**4**	**4**	**0.08**
10.03.2008	45	696	82	40	0.49
		821	56	42	0.76
	average	**759**	**69**	**41**	**0.62**
	st.dev	**88**	**18**	**2**	**0.19**
17.03.2008	52	201	165	95	0.58
		374	95	60	0.63
	average	**288**	**130**	**77**	**0.60**
	st.dev	**122**	**49**	**25**	**0.04**
24.03.2008	59	633	88	53	0.61
		506	133	85	0.64
	average	**570**	**110**	**69**	**0.62**
	st.dev	**90**	**32**	**22**	**0.02**
31.03.2008	66	633	88	53	0.61
		506	133	85	0.64
	average	**570**	**110**	**69**	**0.62**
	st.dev	**90**	**32**	**22**	**0.02**
7.04.2008	73	623	32	21	0.67

		477	73	42	0.59
	average	**550**	**52**	**32**	**0.63**
	st.dev	**103**	**29**	**15**	**0.06**
14.04.2008	80	711	86	46	0.53
		544	68	32	0.47
	average	**628**	**77**	**39**	**0.50**
	st.dev	**118**	**13**	**10**	**0.04**
21.04.2008	87	1377	78	71	0.92
		217	88	55	0.63
	average	**797**	**83**	**63**	**0.77**
	st.dev	**821**	**7**	**12**	**0.20**
28.04.2008	94	1074	70	36	0.51
		718	80	54	0.68
	average	**896**	**75**	**45**	**0.59**
	st.dev	**252**	**7**	**13**	**0.12**
05.05.2008	101	351	136	76	0.56
		128	70	45	0.64
	average	**239**	**103**	**61**	**0.60**
	st.dev	**158**	**47**	**22**	**0.06**

Table 4.R Summary of biofilm parameters in testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	Biofilm thickness	Biofilm density		
			TS	VS	VS/TS ratio
		µm	g l^{-1}	g l^{-1}	-
28.01.2008	3	232	110	78	0.69
04.02.2008	10	263	88	45	0.51
11.02.2008	17	476	95	54	0.57
18.02.2008	24	557	95	53	0.59
25.02.2008	31	521	94	66	0.70
03.03.2008	38	474	109	66	0.62
10.03.2008	45	254	164	97	0.57
17.03.2008	52	733	77	46	0.61
24.03.2008	59	514	79	53	0.70
31.03.2008	66	546	66	40	0.62
7.04.2008	73	487	75	51	0.68
14.04.2008	80	519	80	51	0.67
21.04.2008	87	688	67	48	0.71
28.04.2008	94	544	96	58	0.61
05.05.2008	101	601	78	52	0.68

Table 4.S Summary of biofilm parameters in testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	Biofilm thickness	Biofilm density		
			TS	VS	VS/TS ratio
		µm	g l^{-1}	g l^{-1}	-
28.01.2008	3	524	95	49	0.52
04.02.2008	10	596	62	32	0.54
11.02.2008	17	1275	60	32	0.54
18.02.2008	24	849	54	38	0.70
25.02.2008	31	185	89	61	0.68
03.03.2008	38	489	74	45	0.61
10.03.2008	45	759	69	41	0.62
17.03.2008	52	288	130	77	0.60
24.03.2008	59	570	110	69	0.62
31.03.2008	66	570	110	69	0.62
7.04.2008	73	550	52	32	0.63
14.04.2008	80	628	77	39	0.50
21.04.2008	87	797	83	63	0.77
28.04.2008	94	896	75	45	0.59
05.05.2008	101	239	103	61	0.60

Table 4.T Biofilm viability in testing reactor (experiment 4, Chapter 6)

Date	Day of the experiment	viability [%]
22.02.2008	**28**	40
		10
		19
		22
	average	**23**
	st.dev	**13**
01.04.2008	67	33
		35
		34
		37
	average	**35**
	st.dev	**2**
05.05.2008	101	53
		42
		37
		52
	average	**46**
	st.dev	**8**