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Effects of Reduced Aeration in a Biological Aerated Filter

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by

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ABSTRACT

Aeration is a major part of the operation cost in biological aerated filtration (BAF) systems for wastewater treatment. This thesis investigated the effect of reducing aeration at the City of Windsor's Lou Romano Water Reclamation Plant to find the lowest possible airflow while maintaining a satisfactory ammonia and biological oxygen demand (BOD) in the BAF effluent. A series of tests were conducted at different airflows in cell #7 at the plant to find the lowest possible airflow while maintaining a satisfactory ammonia and biological oxygen demand (BOD) in the BAF effluent. Profiles of temperature, dissolved oxygen, pH, BOD, ammonia and nitrate concentration were measured along the height of the cell and at different time intervals during filtration, at air flow rates varying from 1300 to 1700 m^3/h per cell. This study found that the BOD and ammonium removal were satisfactory at 1300 m^3/h airflow rate.

DEDICATION

The author dedicates this piece of work to his beloved parents who encouraged and sacrificed a lot during his studies.

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LIST OF ABBREVIATIONS

BAF	Biological Aerated Filter
BOD	Biological Oxygen Demand
CBOD	Carbonaceous Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
LRWRP	Lou Romano Water Reclamation Plant
OTR	Oxygen Transfer Rate
OUR	Oxygen Uptake efficiency Rate
SS	Suspended Solids

CHAPTER ONE

INTRODUCTION

1.1 General

A wastewater treatment plant is a facility designed to remove contaminants from wastewater originating from different sources such as households, industries and surface runoff. Different types of treatment systems are available depending upon the influent characteristics of the wastewater and the desired effluent characteristics of the facility. Historically, wastewater treatment consisted of simple screening followed by settling of the solids. However, fine particulate matter and dissolved organic matter are not efficiently removed by these processes. If not removed from the wastewater, this organic matter degrades in the receiving water body, such as a lake or river, and in so doing consumes oxygen. In fact, biological oxygen demand (BOD) is a measure of organic matter in wastewater and a criterion for wastewater effluents. To remove BOD, secondary treatment is added, which is typically a process where the wastewater is aerated to accelerate the decay process and consume the organic matter. The activated sludge process is the conventional secondary treatment process. But this method requires a large treatment area and it works very slowly during high inflow into the system. More recently, regulators of municipal discharges have imposed maximum ammonia concentration limits which cannot be achieved simply by using activated sludge as the secondary treatment.

1.2 Biological aerated filter (BAF)

1.2.1 Overview

Biological aerated filter (BAF) is one of the newest secondary treatment methods. It is able to remove nitrogen (ammonia) as well as organic matter. BAFs are submerged, aerated, fixed-film reactors where biological organisms are used to remove organic matter and ammonia, and suspended solids (SS) are filtered out by granular media. The first commercial full scale BAF was in operation in Soissons, France in 1982 (Wang et al., 2009). After that, a large number of BAF systems were introduced in Europe, Japan and North America.

The granular media is submerged in the reactor and fed wastewater after removal of some solids by primary settling (clarifying). Treated wastewater enters the BAF at the top or the bottom depending upon the design of the plant. Air is diffused upward through granular media during operation. Coarse or fine media is used to facilitate microbial growth in the system. The air promotes the growth of biomass in the voids of the media by providing the required oxygen for the organisms. Simultaneous SS and nitrogen removal can be obtained with upflow BAF reactors. The head loss increases in the media as biomass grows on the granular media and influent SS is trapped. A level of maximum allowable head loss is determined, and after that backwash is required to return the system again to original working condition. A series of air scour and treated water flushes occur during this backwash process.

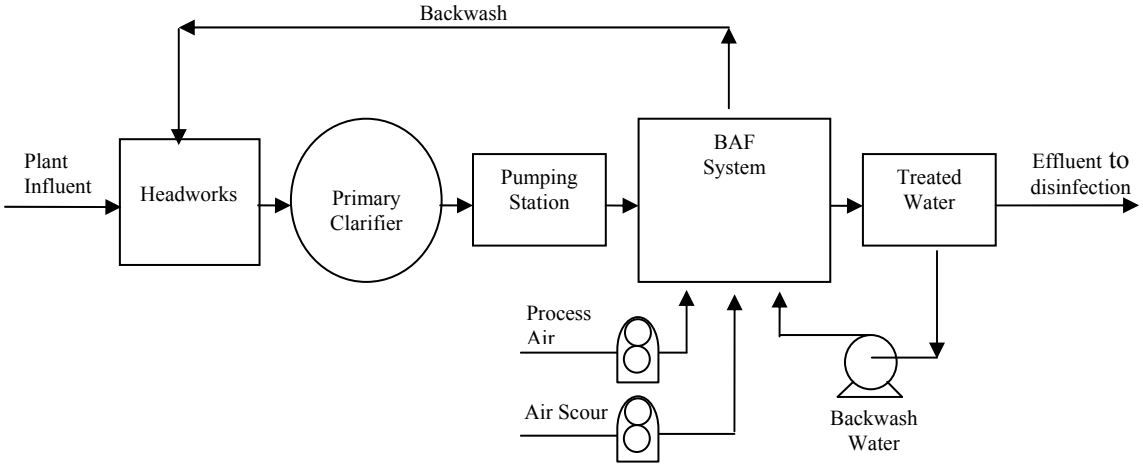


Figure 1.1: Typical BAF wastewater treatment plant

BAF has the following advantages over a conventional activated sludge process:

- no secondary clarifier is required which is cost efficient,
- it requires relatively less space,
- relatively less operator attention is required,
- the BAF can be in operation over a wide range of temperatures and loadings, and

- rapid startup of the system is possible.

However, sufficient knowledge and strong operational control is required by the plant operator. Poor control can cause failure of the whole system.

1.2.2 Degrémont Bofor® (Degrémont Inc., 1991)

Biofor® is the trademark of an upflow single-stage biological aerated filter system introduced by Degrémont Inc. The single stage configuration provides the highest air flow where the highest amount of pollutant is present. The Biofor® installation mainly consists of:

- a set of parallel identical cells made of concrete. They are rectangular pits with approximately 140 m^2 surface area and 6 m of water depth. The number of cells in the plant depends upon the design loading.
- a mechanical setup in the pit for wastewater entrance equipped with a screen.
- a set of diffusers for air flow provided by blowers.
- prefabricated perforated slabs to support the media.
- for the collection of treated and wash water from the reactor, two front mounted surface sloping weirs are installed. These weirs are protected by a material trap to eliminate turbulence during the washing cycle.
- a water collection trough to take away the treated water which is common to four parallel cells and a common backwash water collection trough to take the wash water back to the primary clarifiers.
- the media used by Degrémont Inc. is named “Biolite”. Two types are available- Biolite® 2.7, which are 2.5-2.9 mm in diameter, and Biolite® 3.5, which are 3.2-3.8 mm in diameter. It is a clay-like, baked granular material.

The BAF operation mainly consists of two cycles: a treatment (filtration) cycle and a washing cycle.

In the treatment cycle, primary treated wastewater is introduced into the cell through the feeding channels in the bottom of the reactors. A continuous upflow of process air is

introduced concurrently when the cell is in use. Treated water overflows into the trough and is sent for disinfection.

In the washing cycle, treated water is used to wash the media when either the maximum allowable head loss is achieved or the maximum filter duration has elapsed. During wash the air flow rate is the same as the filtration phase but the water flow rate is almost thrice the normal value. A couple of wash cycles are performed in about 40 minutes. A strong backwash is used once every two weeks, in which double the airflow is used and the water flow rate is about six times normal. Around 10-15 % of the treated water is used for the wash cycle. Then the cell is ready to filter, but if the wastewater flow rate is low it enters "standby" mode. In this mode process airflow is required for 5 minutes per hour in order to give the required oxygen to keep the microorganisms active for future use (called oxygenation).

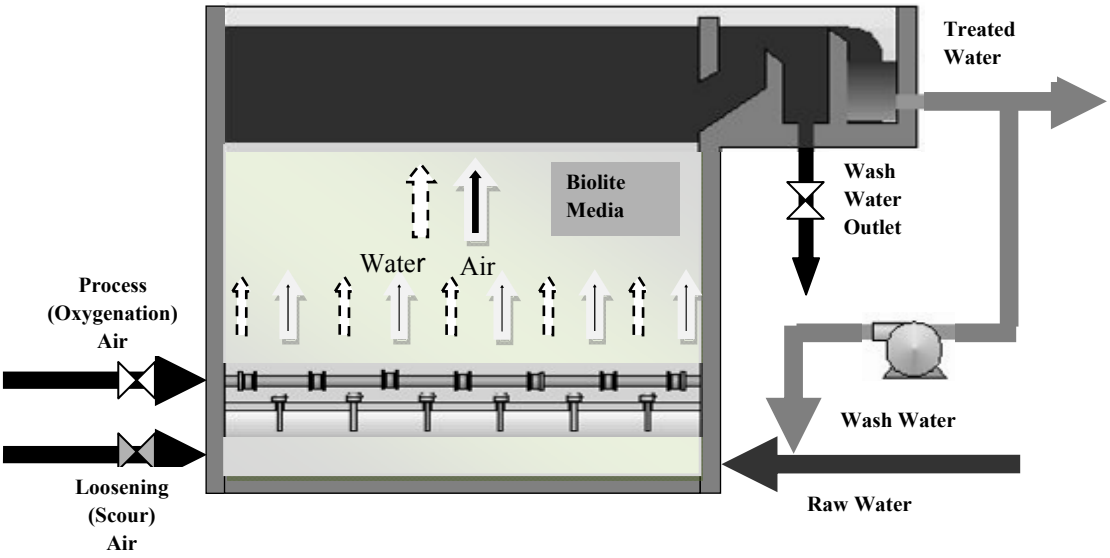


Figure 1.2: BIOFOR® BAF (adapted from Degrémont Inc., 1991)

1.2.3 Lou Romano Water Reclamation Plant (LRWRP)

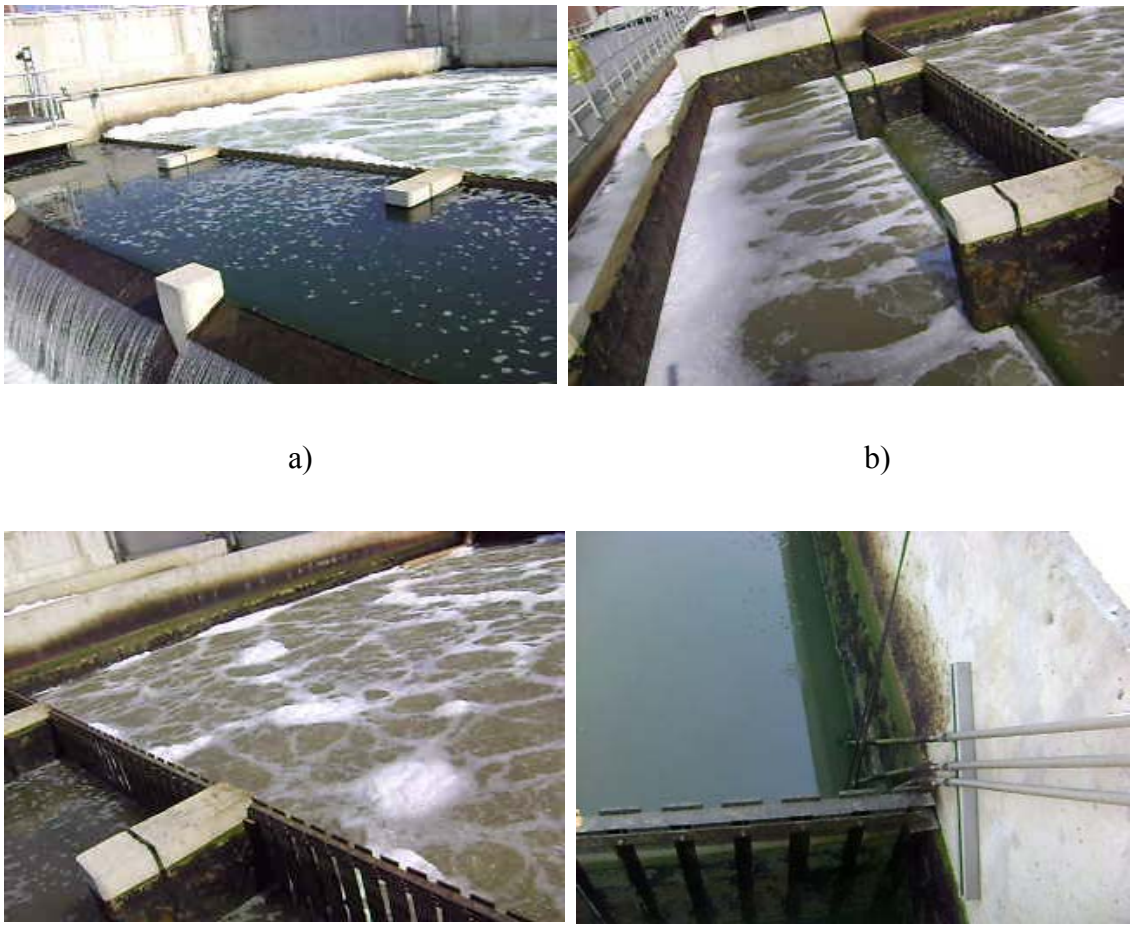
West Windsor Pollution Control Plant was first introduced in 1969. Until 2007, it used chemical precipitation and flocculation in the primary clarifier to obtain an enhanced primary treatment of wastewater. In 1990, the City of Windsor began a pilot study to find the best possible secondary treatment facility. In phase one, four alternatives: biological

trickling filter, rotating biological contractors (RBC), biological aerated filter and modified activated sludge process (ASP) were tested to find the best choice for the City. In phase two, a BAF and a modified ASP were studied further. Phase two started in 2002 and it was concluded that the modified ASP had a comparatively higher cost. Then two types of BAF systems: Biostar® (Biostar Systems Ltd.) and Biofor® (Degrémont Inc.) were tested for the City of Windsor and better results were obtained with the Biofor® system. The secondary treatment expansion started in 2003 by using Biofor® technology and was completed in 2007. The BAF consists of 16 cells, which is the second largest such system in Canada, after Quebec City (52 cells). At present, the plant has an ultimate capacity of 227 MLD. The plant receives wastewater from South Windsor, a combined riverfront interceptor sewer and wastewater from the Town of La Salle.

The surface area for each BAF cell is 140 m^2 with 5.94 m water depth. The settled media height is 3.9 m. The process airflow is variable between 1300 m^3/h and 1900 m^3/h per cell. Biolite® 2.7 media was used in the LRWRP BAF. The average water velocity is 6 m/h for each cell, with a 21 ML/d average treatment capacity. Figure 1.3 shows the LRWRP BAF in operation.

1.3 Objectives

It was observed that the BAF effluent water had a high dissolved oxygen (DO) concentration (>5 mg/L). In a conventional ASP, the water leaving secondary treatment has no more than about 2 mg/L DO, because the biological consumption of the organic matter has been completed at this point. It was felt that the high DO in the BAF effluent was unnecessary, and reducing it could save energy and money through lower aeration blower use. The objective of the current study was to find the effects of reduced aeration in the BAF at LRWRP.



a) b)

c) d)

Figure 1.3: LRWRP BAF cell # 7 in various modes of operation: a) filtration, showing the treated water flowing into the catchment trough; b) backwash, showing the lowered water depth and the wash water entering the wash water trough; c) in standby with oxygenation; and d) in standby without oxygenation showing the sampling ports

1.4 Scope

The scope of this study included finding:

- the BOD and DO values at various height in the cell, under different aeration rates,

- the nitrogen (ammonium and nitrate) values throughout the cell at different heights under different aeration rates,
- the nitrogen mass balance in the cell, and
- the re-aeration coefficient.

CHAPTER TWO

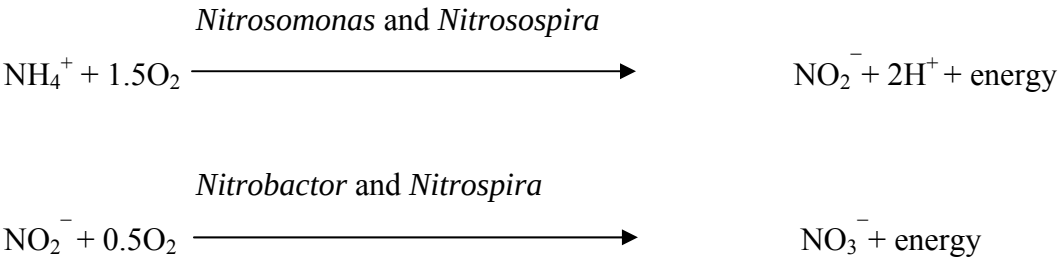
REVIEW OF LITERATURE

2.1 General

BAF's are aerated, fixed, granular, immersed filter beds which carry out two simultaneous functions: organic matter transformation by the biomass which grows on the granular media and suspended particles retention through the same media (Pujol et al., 1992). The focus on BAF has increased significantly by researchers because of its lower consumption of energy and chemicals. In wastewater treatment plants, reduction of space, aeration operation energy and use of chemicals, are the three main factors where a huge cost savings can be possible.

2.2. Nitrogen conversion in BAF

Ammonium ions can be removed from the system in several ways. The common method is to remove nitrogen by nitrification which is a two step process where ionized ammonia is oxidized first to nitrite (NO_2^-) and then nitrite is oxidized to nitrate (NO_3^-). *Nitrosomonas* and *Nitrosospira* oxidize ionized ammonia (ammonia) to nitrite while *Nitrobactor* and *Nitrospira* do the rest (Gerardi, 2006).



In this process, nitrification is used as a prime method to remove ammonia by converting it to nitrate in the water. This requires a high aeration rate to supply sufficient oxygen and maintain sufficient energy needs in the system. Moreover, as nitrifying bacteria can gather very little energy from the nitrification process, their bacterial growth and reproduction is relatively low. Only 0.06 kg of nitrifying bacteria can be produced from every kg of ammonia nitrification (Gerardi, 2006). Another limitation in this process is

that nitrifying bacteria are only active and reproduce between 5°C and 40°C. The best nitrification rate occurs at 30°C but it almost stops below 5°C. Free ammonia loading in the range of 1-5 mg/d/m^3 inhibits selective oxidization and the inhibition highly depends on ammonia concentration and pH, temperature, DO limit, and growth rate of ammonium oxidizers over nitrite oxidizers (Truk and Mavinic, 1989).

The second approach is simultaneous nitrification and denitrification in the system. In this case, aeration energy and chemical use can be reduced effectively as ammonium and nitrite act as electron donor and acceptor respectively (Han et al., 2001). Denitrifying bacteria are facultative anaerobic bacteria which use nitrite and nitrate for degradation of CBOD.

$$6NO_3^- + 5CH_3OH \xrightarrow{\text{Facultative anaerobic bacteria}} 3N_2 + 5CO_2 + 6OH^-$$

Accidental denitrification due to an accidental anoxic condition can happen with poorly settling solids in the BAF. This is referred as “clumping” or “dark sludge rising” (Gerardi, 2006). Within the sludge blanket, facultative anaerobic bacteria use nitrite ions to degrade CBOD which produces N_2 gas. Many of these gases are taken by floc particles and cause buoyancy of the solids, and thus solids rise to the surface.

In a biological aerated filter, nitrogen removal is always economical if ammonia can be nitrified to nitrite and then denitrified in one process. Oxygenation can be reduced 25 % and electron donor requirements are 40 % less. Moreover, the denitrification rates with nitrite ions are usually 1.5-2.0 times faster than with nitrate ions (Abeling & Seyfried 1992). Normally, nitrite accumulation studies are performed by controlling different factors, such as free ammonia concentration, which depends on pH and temperature, dissolved oxygen (DO) concentration (Kuai & Verstraete, 1998, Turk & Mavinic, 1989) and the presence of heterotrophic nitrifiers in the system (Rhee et al., 1997). Around 1.0-5.0 mg/L of NH_3 inhibited from nitrite oxidation (So-Hyun et al., 2000). A recent study revealed that, greater than 95 % ammonium removal was possible (up to 2 kg NH_4^+-N m^-

^{3}/d) and 60 % of it accumulated as NO_2^--N when oxygen was limited to 17 mm/s superficial air velocity in the BAF (So-Hyun et al., 2000).

Denitrification in the BAF can be significantly affected if a high concentration of suspended solids (SS) is present in the effluent. That is why BAF is commonly applied after primary treatment in municipal wastewater systems (Payraudeau et al., 2000, Gilmore et al., 1999). Improper treatment of SS can reduce BAF performance by affecting the mass transfer of oxygen and substrates into the biofilm (Westerman, 2000). The presence of sufficient carbon accelerates denitrification during the nitrogen removal process (Henze, 1991). In most of the cases researchers proposed a nitrification-denitrification process as a two or more stage BAF system (Hong-Duck et al., 2008).

Han et al. (2001) studied the autotrophic nitrification and denitrification characteristics of an upflow biological aerated filter. Their objective was to study the efficiency of a BAF with porous media for nitrification and investigate the possibility of simultaneous nitrification and denitrification without added organic carbon when the oxygen was limited. A laboratory scale upflow BAF with porous polyurethane based media was used to carry out the nitrification of wastewater. The macro-pores had both aerobic and anaerobic zones. The wastewater was loaded at a rate of 1.8 kg NH_4^+/m^3/d. They found that DO concentration increased with height (from the bottom) when the ammonia loading was increased and the nitrification rate increased. This was because air and wastewater were both introduced concurrently at the bottom. The average values of loading measured at the bottom were 0.7-1.0, 1.4-1.8 and 1.8-2.5 mg/d/m^3 at superficial air velocities of 0.1, 0.2 and 0.3 cm/s, respectively. They were able to achieve 90 % nitrification efficiency as compared to 80-90 % efficiency achieved by Pujol et al. (1994). They found that N was unbalanced in the system and so tried to estimate the nitrogen loss in the system by calculating the total mass balance of NH_4^+-N, NO_2^--N, NO_3^--N and nitrogen converted to biomass. The estimated loss was low at lower loadings, but around 40 % NH_4^+-N was lost at higher loadings. They hypothesized that simultaneous nitrification and denitrification were happening in the system in the anoxic micro-zones in the centre of sludge floc or in the inner part of the bioflim near the media.

In the LRWRP, total ammonia is tested twice a week which gives approximately 120 data points for 2009. Overall, 76 % ammonia removal was achieved with an air flow rate of 1300 m^3/h to 1700 m^3/h per cell (LRWRP plant data, 2009).

Media height is one of the controlling factors which influence the efficiency and capital cost of a biological aerated filter (BAF). An experimental study was done by Hu and Wang (2005) to find the optimum media height for carbon oxidation and nitrification in a down-flow aerated filter. The change of organic carbon content and ammonia concentration was observed in order to find the distribution of heterotrophic and nitrifying populations with different levels of media height. A cylindrical bio-filter of 2.8 m height and 0.15 m outside diameter was installed in the lab where raw domestic wastewater with two different levels of loading were used to feed the BAF containing a 2 m depth of ceramic media of 2-5 mm diameter. A Plexiglas reactor with 10 sampling ports at intervals of 200 mm in height was used. Filter backwashing was carried out with clean water and air from the bottom of the filter for 15-20 minutes. A steady-state operation was obtained by feeding a stream of constant quality into the reactor.

Their experiment revealed the effect of media height on suspended solids (SS) removal, COD removal, DO concentration, NH_4^+-N concentration, and organic and ammonia volume loading in the BAF. Most of the SS were removed by the upper 600 mm of media. The middle and bottom part had very little effect on SS removal. The highest increment of COD removal was found on the top 600-800 mm of media height. The activity and quantity of biomass was higher at the top of the filter, so degradation capacity was also high in the first 600-800 mm of media. The DO concentration was highest around 800 mm from the top for both levels of loading. From 0-800 mm in height, the DO concentration was decided by the organic concentration in the sewage. As the organic concentration decreased gradually along the flow direction the oxygen consumption decreased. After 1.0-1.5 m from the top, the DO concentration depended on bubble residence time in the media. The longer the bubble residence time, the higher was the DO concentration. Near the bottom of the column where aeration started, the bubble residence was low, which caused a lower DO concentration. The NH_4^+-N removal rate was also higher at 400-800 mm from the top with a maximum of 96.4 % removal at 800

mm height. The NH_4^+-N removal efficiency was greatly influenced by the DO concentration, with the DO concentration increasing after a lag of about 400 mm, the removal efficiency increased at the top 1.0 m of the bio filter. This study concluded that around 80-90 % efficiency could be achieved within the first 1.0 m of media height of the proposed bio filter. Efficiency was higher for higher organic influent loading.

Lemoine et al. (2006) did an extensive study to find the amount of aeration for a simultaneous nitrification and denitrification system by using an internal model approach. They ran a pilot plant where two identical reactor columns (30 cm diameter and 5 m in height) were used with polystyrene bead media. They used city of Maisons-Laffitte wastewater directly as feed after passing it through the primary settler. Continuous monitoring was conducted for DO, temperature, NH_4^+-N and NO_3^--N for inlet and outlet. The loading varied between 0.3-0.6 kg NH_4^+-N/d/m^3. A calculation of the ammonium load to be eliminated resulted in an estimation of the air flow velocity to be applied and this was controlled dynamically. A retroactive loop corrected this prediction in order to reach exactly the desired set point. This approach was carried out and tests were continued at the pilot plant scale for a period of 18 months. They found that a poorly adaptive control system can cause a strong decrease in treatment efficiency. Overall nitrification efficiency for different types of BAF is given in Table 1.

Table 2.1: Nitrification efficiency for different types of BAF

BAF Type	Air velocity	Ammonium Loading	Ammonia removal efficiency
Upflow-laboratory scale (Hyun et al.,2000)	61.2 m/h	2.0 kg/d/m^3	95 %
Four stage-laboratory scale(Hong et al.,2008)	12 L/min	1.04 kg/d/m^3	96 %
Downflow-laboratory scale (Harris et al.,1996)	6 m/h	0.41 kg/d/m^3	>90 %
Downflow-laboratory scale (Stensel et al.,1988)	6 m/h	0.41 kg/d/m^3	88 %
Downflow-pilot plant, (Pujol et al.,1992)	NA	1.68 kg/d/m^3	55 %
Upflow-pilot plant, (Pujol et al.,1992)	NA	1.84 kg/d/m^3	58 %
Downflw-laboratory scale (Hu and Wang ,2005)	0.24 m/h	0.3-0.55 kg/d/m^3	>80 %
LRWRP	6 m/h	0.3 kg/d/m^3	76 %

2.3 Aeration and oxygen transfer efficiency

The classic theory of oxygen transfer can be applied to the oxygen movement from the sparged gas to the biomass through dissolution into the bulk liquid. Here, the driving force is the DO gradient between the two phases which causes the oxygen transfer (Harris et al, 1996). A number of models can be found which predict the movement between the two phases, of which the most common is the two-film theory by Lewis and Whitman (1924). This method considers diffusion of oxygen through both gas and liquid film layers at the interface. The oxygen mass transfer coefficient, K_{La}, is used to find the oxygen transfer rate (OTR) through the system. The OTR is calculated using Equation 2.1 (Harris et al, 1996).

$$OTR = dC/dt = \alpha K_{La} (\beta C^* - C) - r_m \qquad \text{[Eqn. 2.1]}$$

where,

OTR = oxygen transfer rate.

dC/dt = the rate of change of oxygen concentration.

C* = saturated oxygen concentration.

C = dissolved oxygen concentration in water.

K_{La} = oxygen transfer coefficient.

α = wastewater K_{La} to clean water K_{La} ratio.

β = wastewater to clean water oxygen concentration ratio.

r_m = continuous removal of DO from the liquid by microorganisms.

An approach to find the volumetric re-aeration coefficient, K_a, is described in the current study in the Results and Discussion section. K_a is dependent upon several factors such as temperature, the depth of aeration, bubble size and mass air flow rate (Fujie et al., 1992). This applies to a suspended growth system but a BAF is an attached growth system. Recent studies by Canziani (1988) and Reibar and Stensel (1985) found that K_a can be computed for the BAF system if a factor of 2.0 to 2.5 is applied to K_a obtained by using conventional aeration calculations. Oxygen transfer efficiency (OTE) can be increased by

increasing the bubble detention time, number of bubbles, and distance travelled (Fujie et al., 1992).

The city of San Diego, California has a BAF plant at the Point Loma wastewater treatment plant. An experimental study was conducted by Stenstrom et al. (2008) to find the oxygen transfer efficiency in a pilot plant at this location. Two types of media- Biofor® and Biostyr® were used in two 4 m high columns with 4 sampling ports in the Biofor® and 6 in the Biostyr®. Both of them were down-flow BAF reactors. An off-gas testing method was used to measure the oxygen transfer efficiency. This technique is based on performing an oxygen content measurement on the off-gas stream leaving the top of the reactor. A mass balance between the air feeding line and the off gas was performed. Submerged hoods of 2.5 m^2 area were used to obtain oxygen transfer rates at different heights. DO and COD concentrations were measured at ports at various heights and a mass balance was performed to relate the oxygen transfer efficiency to DO and COD. The mass balance was performed by using Equation 2.2.

$$OUR = Q [COD_{in} - COD_{out} + DO_{in} - DO_{out} + 4.5 (NH_4\text{-}N_{in} - NH_4\text{-}N_{out})] - (\text{CODconverted to cell mass}) \quad \text{[Eqn.2.2]}$$

where OUR = oxygen uptake efficiency rate

The result showed that both DO and COD declined in both types of media with increasing distance travelled. The only deviation was the first point above the feed line in the Biofor® due to higher COD caused by biosolids. They found a higher OUR than typically achievable at the same process-water depth with a fine-pore aeration system. This efficiency was likely due to the higher bubble residence time in the column from bubble hold-up in the media. Leung et al. (2006) have shown that the mass transfer rates triple when doubling the gas holdup volume. The OUR calculated by mass balance was not accurate enough to find the oxygen transfer rate in Biostyr® reactors. The calculated rate was lower than the actual one. But in the case of Biofor®, the calculations were more accurate. The oxygen transfer efficiency per metre was better (4-6 %) than typical in a fine pore aeration system which typically has 3-5 % efficiency. The DO concentration for

both of the pilot plants decreased with increasing height. At low air flow rate, the DO at the top was much lower than at the bottom.

The oxygen transfer characteristics in an up-flow BAF were studied by Leung et al. (2006). The effects of water flow rate, air flow rate, liquid temperature and gas holdup on the oxygen transfer coefficient were evaluated. The prime concern of the study was to enable the BAF aeration process to be economically optimized. A 100 mm diameter and 1.3 m high bench scale upflow BAF column was fabricated which had liquid sampling ports at regular intervals of 51 mm. The column was constructed from two sections of clear acrylic pipe separated by a flange. The bottom section of the column acted as a water reservoir, where as the top section had a gravel media below clay media. Two different sizes of media, 2.7 mm (clay media) and 3.5 mm (gravel media) were used for the experiment. Dissolved oxygen concentration at each sampling port was determined with an oxygen probe. The porosity of the clay material was determined volumetrically.

They used several assumptions to determine the oxygen transfer co-efficient:

1. The flow of water through un-fluidized media was a plug flow.
2. *p*H, porosity, temperature and influent dissolved oxygen concentration were constant.
3. The entire system was in steady state.

The dependence of K_{La} on temperature and gas and liquid velocities was determined by using empirical equations from Danil and Gulliver (1988) and Alexander and Saha (1976), respectively. Wastewater and clean water correction factors α and β were assumed to be 1.0 because Reiber and Stensel (1985) found the ratio to be almost 1.0 in the case of a BAF. However, an overall correction factor had to be applied for the BAF. The experimental results showed that oxygen transfer coefficients increased with both the liquid and gas velocity. The increase in water temperature resulted in an increase in oxygen transfer coefficient.

2.4 Ammonia stripping

Ammonia can be stripped out from the wastewater by controlling factors like pH, air flow rate and temperature in the system. This approach for ammonia removal is unconventional and many researchers are now working on it. Stripping of ammonia is very common in BAF wastewater treatment plants due to aeration but a low amount can be expected with normal air flow rate and pH below 10.0 (Shpirt, 1981).

Shpirt (1981) tried to find the rate of ammonia removal from wastewater by diffused aeration. A bench scale reactor column was constructed from a 107 mm diameter Plexiglass tube with two types of diffusers (course and fine). Tap water with 50-100 mg/L-N as NH_4Cl was used as wastewater and the temperature and pH were controlled at 200°C and 11.5, respectively. A model for ammonia desorption was developed by defining the overall mass transfer coefficient of ammonia transfer as a function of air loading rate, diffuser submersion, diameter of air bubbles, kinematic coefficient of viscosity and coefficient of diffusivity. Downing (1958) and Baylay (1967) made an assumption that the removal rate of gas was directly proportional to air flow rate. But Shpirt (1981) found that ammonia stripping was largely dependent on the type of diffuser used in the system: fine bubble aeration was twice as effective as coarse bubble aeration for ammonia striping from wastewater.

CHAPTER THREE

MATERIALS AND METHODS

3.1 General

The DO, pH and temperature were measured in the field and ammonium, nitrate, COD in the laboratory at the University of Windsor. Samples were taken between February, 2010 and July, 2010. The wastewater temperature was an average of 11^{o}C in February and March, 17^{o}C in April and May and 22^{o}C in June and July. The motivation was to find the effect of temperature on the properties of wastewater with this variation of temperature in different times of the year.

The nominal air and water flow rates per cell were recorded from the plant control room during the sampling. The actual air flow rate depended on the number of cells in operation, water flow rate in the cell and pressure head in the cell. The nominal air flow rate was used in the calculations. The nominal airflow varied from 1300 m^3/h to 1700 m^3/h. The air blower's controller was set to operate within this range by service provider Degrémont Technologies Ltd. which limited the lowest nominal airflow to 1300 m^3/h. The water flow rate was calculated from the total inflow in the cells divided by the number of cells in operation for specific periods of time.

3.2 Sample Collection

Sample collections were performed between 8:00 a.m. and 2:30 p.m. to reduce the fluctuation in wastewater inflow in the BAF. Moreover, it conformed to the authorized admissibility into the plant during the working hours. Sampling ports were installed at (25 %, 50 %, and 75 %) heights from the bottom of cell # 7. For each port, a ½ inch plastic pipe was placed in a ¾ inch PVC pipes attached to the BAF cell wall by using a clamp and screw (Figure 1.3d). A Teledyne ISCO auto sampler was used to collect the

grab samples. The sampler could collect sample at 93-167 mL/min depending on the pressure height of the sampling port.

Table 3.1: Sampler characteristics

% height of the cell (from bottom)	Sampler speed (mL/min)	Required time for 250 mL(min)
25	93-100	2.5-3.0
50	112-119	2.0-2.5
75	142-167	1.5-2.0

500 mL NALGENER® plastic containers were used to collect the samples, which conform to the recommended types of container for storing samples for NH_4^+, NO_3^-, and COD test (APHA et al., 2005).

During the winter, sampling ports were defrosted by using hot water to ensure continuous flow through the sampling tubes. Plastic caps were used to prevent snow falling in the sampling ports.

3.3 Field tests

3.3.1 DO and Temperature

A Thermo Scientific Orion 5-Star plus DO/Temperature Meter supplied with a DO probe was used to measure DO directly in the field. Temperature was recorded at the same time with the same meter. Samples were drawn into a 500 mL plastic container as described in Section 3.2 and measured immediately for DO and temperature on the service platform beside the BAF cell. The sample was not stirred while these parameters were being measured. The accuracy of the meter ±0.02 mg/L for DO and ±0.1ºC for Temperature

3.3.2 pH

A Thermo Scientific Orion 5-Star plus pH meter supplied with pH probe was used to measure pH directly in the field. A buffer pH solution supplied with the meter was used

to calibrate the probe each day before using in the field. The pH was tested in the LRWRP Control Room immediately after the DO and temperature were measured for the samples.

3.4 Laboratory tests

3.4.1 Sample Preservation (APHA et al., 2005)

Collected samples were preserved with 20 % H_2SO_4 onsite to reduce the possible loss of NH_3. H_2SO_4 was added to bring the pH down to 2.0. This essentially stops all the chemical reactions in the samples and they can be further preserved by refrigerating up to 28 days. Usually the samples were analyzed within 24 hours of the sample collection.

3.4.2 COD (Standard Method 5220, APHA et al., 2005)

Considering the high number of samples to be tested, the closed reflux colorimetric method (5220 D) was chosen with some modification. The expected range for COD was from 10 mg/L to 300 mg/L. The motivation for choosing this method from three available Standard Methods is described in Table 3.2.

Table 3.2: COD test methods, range and suitability to test

Test method	Range	Suitability
Open Reflux Method (5220 B)	5 mg/L-1000 mg/L	precise
Closed Reflux Titrimetric Method (5220 C)	40 mg/L-400 mg/L	economical
Closed Reflux Colorimetric Method (5220 D)	20 mg/L-400 mg/L	economical and convenient
Modified Closed Reflux Colorimetric Method (5220 D)	12 mg/L-400 mg/L	economical, convenient and can measure lower range

3.4.2.1 Principle

Almost all types of wastewater organic materials can be digested in a mixture of chromic and sulfuric acids. When a sample is refluxed, it is digested and a material having a

chemical oxygen demand in the sample is oxidized by dichromate ions ($Cr_2O_7^{2-}$). In dichromate Cr^{7+} transforms to Cr^{3+} and both of them absorb in the visible light region. Cr^{7+} has a high absorption at 420 nm and Cr^{3+} absorbs in the 600 nm regions. When the COD value is less than 125 mg/L, the decrease in absorption of Cr^{7+} is measured. For a COD concentration between 100-900 mg/L the increase in Cr^{3+} is measured. In this research, COD values were between 10-400 mg/L. Therefore, initially the absorptions at both wavelengths were measured and it no distinct difference was observed between the lower and higher ranges of COD. The sample dilution technique was used to reduce the COD of all samples below 125 mg/L and the reduction in Cr^{7+} was used to determine the COD.

3.4.2.2 Interference and Limitation

The method is suitable for concentrations as low as 25 mg/L, and below that the method is qualitative rather than quantitative. However, the limit of detection was found to be lower during actual tests (Section 3.4.2.5).

3.4.2.3 Apparatus and Reagents

a. Apparatus

1. Digestion vessels 20 × 100-mm with TFE-lined screw caps
2. Block heater or similar device to operate at 150 ± 2°C, with holes to accommodate digestion vessels.
3. Spectrophotometer-Cary 50 UV/VIS
4. Centrifuge – Beckman Coulter, Allegra X-15R

b. Reagents

1. Digestion solution, low range:
    - 500 mL distilled water
    - 1.022 g $K_2Cr_2O_7$, primary standard grade, previously dried at 150°C for 2 hour
    - 167 mL concentrated H_2SO_4
    - 33.3 g $HgSO_4$

- dissolved, cooled to room temperature, and diluted to 1000 mL with distilled water.

2. Sulfuric acid reagent:

- Ag_2SO_4, reagent grade, powder
- Concentrated H_2SO_4 at the rate of 5.5 g Ag_2SO_4/kg H_2SO_4.
- This took 2-3 days to dissolve.

3.4.2.4 Procedure

a. Treatment of samples:

In a 20 x 100 mm Culture tube, 2.5 mL sample, 1.5 mL digestion solution and 3.5 mL sulfuric acid reagent were taken. A pipette was used to place the correct amount of sample in the culture tube and the digestion solution was added. The sulfuric acid reagent was run carefully down the inside of the vessel in such a manner that an acid layer was formed under the sample-digestion solution layer. The tubes were capped tightly with a PTF lined cap and inverted several times to mix completely. The tube was digested in the block heater for up to 2 h, and then cooled to room temperature. A blank (2.5 mL distilled water instead of sample) was run with every day's batch of tests. It is critical that the volume of each component be known and that the total volume was the same for each reaction vessel.

b. Measurement of dichromate reduction:

To settle the suspended solids, a centrifuge (15 minutes at 3500 rpm) was used to create an optically clear path through the tube. Absorption was measured for each sample blank and standard at 420 nm. All samples, blanks, and standards were measured against this solution. The absorption measurement of an undigested blank containing dichromate, with reagent water replacing sample, gave the initial dichromate absorption. Any digested sample, blank, or standard that had a COD value gave a lower absorbance because of the decrease in dichromate ion. The difference between absorbance of a given digested sample and the digested blank was a measure of the sample COD.

c. Preparation of calibration curve:

Four standards of potassium hydrogen phthalate solution were used to find the COD equivalents to cover the 12.5 mg/L-250 mg/L COD range. Standards were digested as samples and absorbance values were recorded. When standards were run, differences of digested blank absorbance and digested standard absorbance versus COD values were plotted for each standard. This calibration curve (Figure 3.1) was used to determine the COD from the absorbance found for the sample.

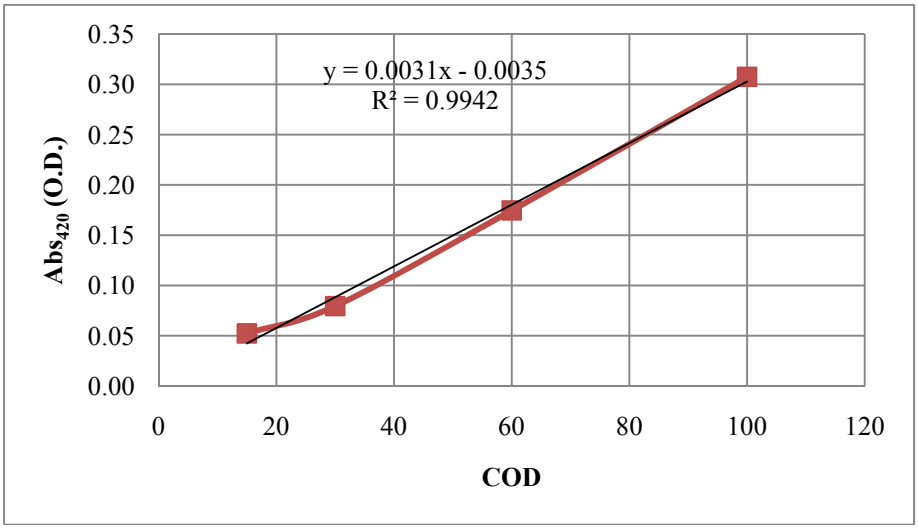


Figure 3.1: Typical COD calibration curve for Test 1

3.4.2.5 Method Detection Level and Uncertainty of the test

According to the Standard Method 1030 C (APHA et al., 2005), if the degrees of freedom is (7-1) =6, at the 99 % level, the product of 3.14 times the standard deviation (SD) is the desired method detection level. Two different samples were tested seven times each to find a method detection level for the test. For COD, the method detection level (MDL) was determined as 2.4 mg/L (Table 3.3).

Table 3.3 Method detection level and uncertainty of the COD

	COD mgO_2/L							SD (mg/L)	MDL (mg/L)	Avg. MDL (mg/L)	Uncertainty of the test (±)(mg/L)
Sample 1	50.04	51.72	51.00	50.56	49.52	50.64	50.16	0.71	2.24	2.44	1.56
Sample 2	22.28	22.08	24.40	23.20	22.92	23.48	23.96	0.84	2.65		

According to the Standard Method, 1030 B (APHA et al., 2005), at 95 % confidence the degree of uncertainty for the test method is twice the standard deviation (SD). For COD the uncertainty of the test was ± 1.56 mg/L.

3.4.3 NH_3 (Standard Method 4500-NH_3, APHA, 2005)

As a large number of samples were to be tested with a low concentration of ammonia, the closed ammonia selective electrode method was chosen. The expected range for NH_3 was from 0.5 mg/L to 25 mg/L. The motivation for choosing this method from the two main available standard methods is described in Table 3.4.

Table 3.4: NH_3 test methods, their range and suitability

Test methods	Range	Suitability
Titrimetric Method (4500-NH_3 C)	>5mg/L	precise
Ammonia selective electrode method (4500-NH_3 D)	0.3 mg/L-1400 mg/L	Economical, lower range, less time consuming

3.4.3.1 Principle

The ammonia electrode uses a hydrophobic (water repelling) gas permeable membrane to separate a sample solution from the electrode internal solution. Dissolved ammonia in the sample will pass through the membrane until the partial pressure of ammonia is equalized. The ammonia gas reacts with the internal filling solution creating an electrical current which is be proportional to the ammonia nitrogen concentration. This method

measures the total ammonia in solution, whether it exists as NH_3 or NH_4^+. So, in this thesis the term ammonia (NH_3) will be used to describe the total ammonia.

3.4.3.2 Interference and Limitation

Mercury and silver interfere by complexion with ammonia. This possibility is removed by using EDTA solution.

3.4.3.3 Apparatus and Reagents

a. Apparatus

1. Ammonia selective electrode - A Orion® 9512HPBNWP high performance ammonia selective electrode.
2. pH electrode
3. Magnetic stirrer (Thermally insulated)
4. TFE coated stirring bar

b. Reagents

1. Ammonia free distilled water
2. NaOH-10N
3. NaOH/EDTA solution -10N

   400 g NaOH is dissolved in 800 mL water, 45.2 g ethylenediamineteraacetic acid, tetrasodium salt, tetrahydrate ($Na_4EDTA{\cdot}4H_2O$) was added stirred, dissolved, cooled and diluted to 1000 mL.

4. Stock ammonium chloride solution

3. 819 g anhydrous NH_4Cl (dried at 100°C) was dissolved in water and diluted to 1000 mL.

3.4.3.4 Procedure

a. Preparation of standards:

A series of standard solutions was prepared covering the concentrations of 1000, 100, 10, 1, and 0.1 mg NH_3-N/L by making decimal dilutions of stock NH_4Cl solution with water.

b. Preparation of standard curve:

Exactly 100 mL of each standard solution was placed in a 150-mL beaker. Then the electrode was immersed in the standard of lowest concentration and mixed with a magnetic stirrer. The stirring speed was maintained as low as possible to minimize possible ammonia loss from the solution. The same stirring rate and a temperature of about 25°C were maintained throughout the calibration and testing procedures. To do this, 1 mL of 10N NaOH /EDTA solution was added to raise the pH above 11. A stable millivolt reading in the electrode was recorded. This procedure was repeated for all the standards, proceeding from lowest to highest concentration. A calibration graph was plotted as shown in Figure 3.2.

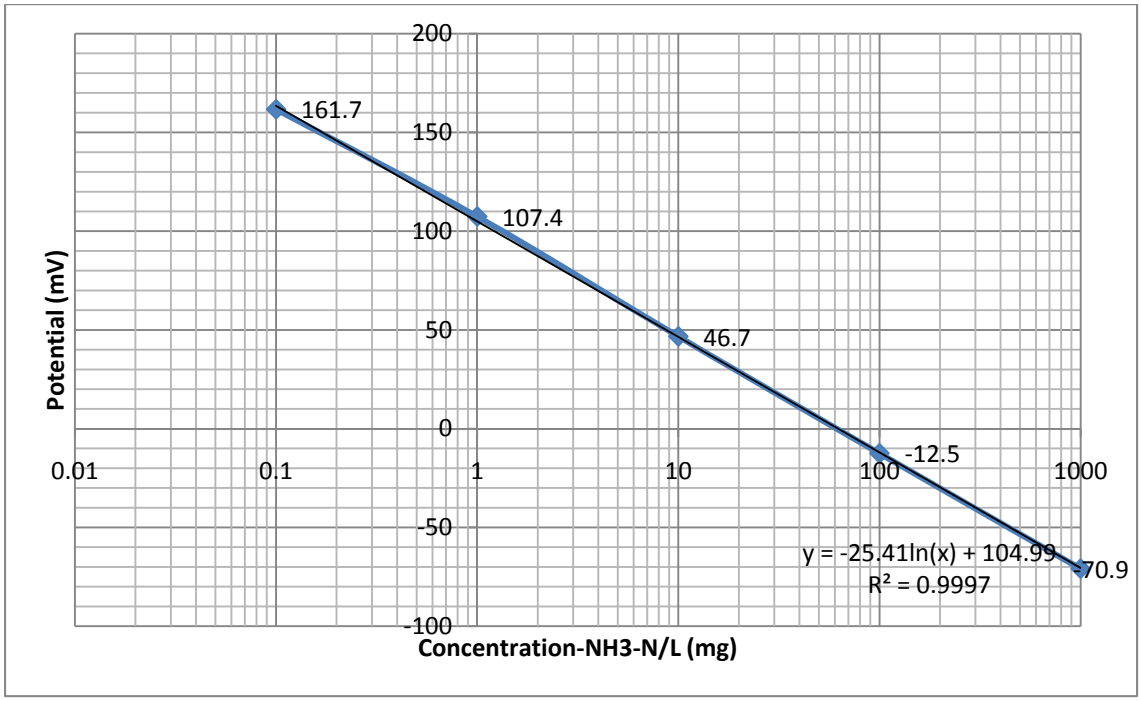


Figure 3.2: Typical NH_3 calibration curve during Test-1

c. Measurement of samples:

The same procedure was followed for samples where 100 mL of sample was added instead of standard solution in the 150 mL beaker. The NH_3-N concentration was calculated from the calibration curve.

3.4.3.5 Calculation

$$\text{mg of } NH_4\text{-N/L} = A \times B \times (100+D)/(100+C)$$

where:

A = dilution factor=1.0

B = concentration of NH_3-N/L, mg/L, from calibration curve,

C = volume of 10N NaOH added to calibration standards, mL, and

D = volume of 10N NaOH added to sample, mL.

3.4.3.6 Method Detection Level and Degree of Uncertainty

For the current analysis, the method detection level (MDL) was calculated to be 0.17 mg/L and the uncertainty was ± 0.11 mg/L (Table 3.5).

Table 3.5 Method detection level and uncertainty of the ammonia test

	NH_3-N mgO_2/L							**SD (mg/L)**	**MDL (mg/L)**	**Avg. MDL (mg/L)**	**Uncertainty of the test (±) (mg/L)**
Sample 1	2.09	2.12	2.04	2.05	2.09	2.15	2.13	0.04	0.12	0.17	0.11
Sample 2	5.60	5.68	5.63	5.60	5.59	5.54	5.46	0.07	0.22		

3.4.4 NO_3^- (Standard Method 4500-NO_3, APHA, 2005)

3.4.4.1 Principle

In the NO_3^- ion electrode method, a selective electrode is used to develop a potential across an inert membrane which holds in place a water-immiscible liquid ion exchanger.

3.4.4.2 Interference and Limitation

Erratic responses have been noted where pH is not constant between pH 3-9. As the electrode responds to NO_3^- activity rather than concentration, ionic strength must be kept constant in all the samples and standards. This problem was minimized by using a buffer solution. This solution contained:

1. Ag_2SO_4 to remove Cl^-, Br^-, I^-, S_2^-, and CN^-
2. Sulfamic acid to remove NO_2^-
3. pH 3.0 acid to eliminate HCO_3^- and to maintain a constant pH and ionic strength
4. $Al_2(SO_4)_3$ was added to remove complex organic acids.

3.4.4.3 Apparatus and Reagents

a. Apparatus

1. pH meter (Thermo Scientific Orion 5-Star plus).
2. Combined electrode - a combined double junction half cell and nitrate ion electrode is required. An Orion 9707BNWP ion plus Sure-Flow electrode was used.
3. Magnetic stirrer: TFE-coated stirring bar.

b. Reagents

1. Nitrate-free water: distilled water was used

2. Stock nitrate solution:

Potassium nitrate (KNO_3) was dried in an oven at 105°C for 24 hour. Exactly 0.7218 g was dissolved in water and diluted to 1000 mL. Then the solution was preserved with 2 mL $CHCl_3$. This solution is stable for at least 6 months.

3. Standard nitrate solutions:

1.0, 10.0, and 50.0 mL amounts of stock nitrate solution were diluted to 100 mL with water to obtain standard solutions of 1.0, 10, and 50 mg NO_3^--N/L, respectively.

4. Buffer solution:

Exactly 17.32 g $Al_2(SO_4)_3 18H_2O$, 3.43 g Ag_2SO_4, 1.28 g H_3BO_3, and 2.52 g sulfamic acid (H_2NSO_3H) were dissolved in about 800 mL water. The pH was adjusted to 3.0 by slowly adding 0.10 N NaOH. Then the solution was diluted to 1000 mL and stored in a dark glass bottle to block any photosynthetic reaction.

5. Sodium hydroxide, NaOH, 0.1N.

3.4.4.4 Procedure

a. Preparation of calibration curve:

Exactly 10.0 mL of 1 mg NO_3^--N/L standard was transferred to a 50-mL beaker and 10 mL buffer was added. The solution was stirred with a magnetic stirrer. The electrode was immersed and a millivolt reading was recorded after the reading become stable (approximately 1 minute). The same procedure was repeated for 10-mg NO_3^--N/L and 50-mg NO_3^--N/L standards. Then the measurements are plotted on semi logarithmic graph paper as shown in Figure 3.6.

Table 3.6: Sample nitrate calibration chart

ppm nitrate as N	Electrode potential (mV)
0.1	81.3
1	72.1
3	59.2
10	35.6
30	12.3
50	-1
100	-21.2

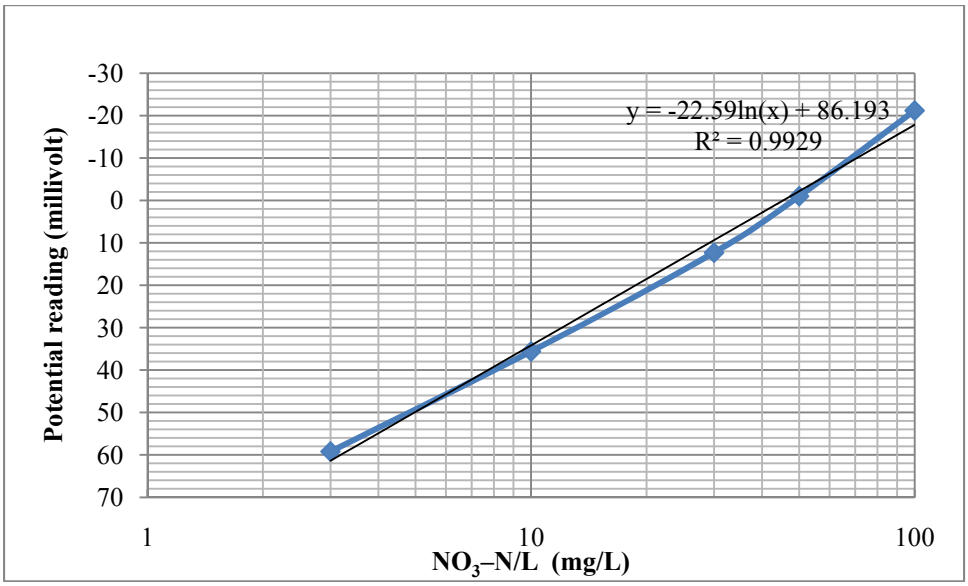


Figure 3.3: Typical NO_3^- Calibration curve during Test-1

b. Measurement of sample:

Exactly 10.0 mL of sample was transferred in to a 50-mL beaker, 10 mL buffer solution was added, and the mixture stirred for 1 min with a magnetic stirrer. The potential reading was recorded and the ion concentration with electrode concentration was found from the calibration curve. Both standards and sample were measured at room temperature.

3.4.4.5 Method Detection Level and Degree of Uncertainty

For the current test, the method detection level (MDL) was calculated to be 0.12 mg/L and the uncertainty was ± 0.08 mg/L (Table 3.7).

Table 3.7 Method detection level and uncertainty of the NO_3^- test

	NO_3^- mgO_2/L							SD (mg/L)	MDL (mg/L)	Avg. MDL (mg/L)	Uncertainty of the test (±) (mg/L)
Sample 1	1.49	1.39	1.42	1.39	1.45	1.46	1.42	0.04	0.12	0.12	0.08
Sample 2	0.94	0.93	0.86	0.94	0.85	0.88	0.91	0.04	0.12		

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 General

LRWRP monitors BOD_5 at various locations in the plant on a semi-weekly basis. However, the BOD test is a complex and time consuming, especially when a huge number of samples needs to be analyzed. In order to compare the COD values in this thesis to LRWRP BOD values, a common practice is to establish a relation between COD and BOD_5 for a specific wastewater (Eckenfelder, and Grau, 1998). The COD tests were performed on grab samples from cell #7 of the BAF at LRWRP.

Table 4.1: COD and BOD_5 correlation

Test Date	**COD (mg O_2/L)**	**BOD_5 (mg O_2/L)**	**COD/BOD_5 ratio**
February 20,2010	130	23	5.65
February 27,2010	178	33	5.39
March 12,2010	210	35	6.00
March 26,2010	170	31	5.48
April 30,2010	172	30	5.73
May 21,2010	160	29	5.52
May 28,2010	156	27	5.78
		Average	5.65

An average value of 5.65 was found for the COD to BOD_5 ratio. This value varies from 3.33 to 10.0 for the effluent wastewater (Metcalf and Eddy, 2004). This correlation was used to calculate the BOD_5 from the measurement of COD.

4.2 Results

Table 4.2 shows the results of all analyses conducted in the field on different dates at different depths in the filtration bed. Table 4.3 shows the analyses of the same samples conducted in the laboratory.

4.3 Analysis

4.3.1 BOD change in cell

Figure 4.1 shows the decrease in BOD at different times of operation as the wastewater passes through the cell. Initially (0 minute), the concentration profile is flat, because there is no water flow through the cell. Then from 30 to 120 minutes run time a definite pattern is observed. Note that BOD concentration decreased more rapidly in the first quarter of the cell as compared to the rest of the cell.

Also, it is observed that effluent DO is always higher than effluent BOD during filtration when the nominal airflow was 1700 m^3/h. The BOD removal efficiency of the cell increased with time. After 30 min the effluent BOD is same as the effluent DO, whereas after 60 minutes, it happened at 82 % height. After 120 minutes the crossover occurs at 75 %. This means that there was sufficient DO in the effluent to oxidize the BOD after it left the BAF. Actually, there is little oxidation of BOD after the BAF because the bulk of the heterogeneous bacteria are in the BAF so little decrease in BOD takes place after BAF. The BOD effluent standard 13 mg/L (CH2M Gore and Storrie Ltd., 1996) was met by the time the effluent had passed through about 40 % of the height of the BAF so there was no need for further oxidation. In effect, there was always an excess of DO in the secondary effluent with respect to oxidization of BOD.

Table-4.2: Test results parameters- measured in the field

Cell-7		Height (from bottom) (m)	Nominal Air Flow/cell (m^3/h)	Water flow/cell (ML/d)	pH				Temperature (^oC)				DO (mg/L)			
Test Number	Date				0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
1	Feb-14-2010	0.00	1700	20.71	7.89	7.64	7.65	7.65	10.2	10.4	11.2	11.8	5.62	8.64	7.27	8.23
		1.49		20.71	7.26	7.89	7.94	8.33	10.1	10.6	11.6	11.4	6.32	8.51	7.98	9.01
		2.97		20.71	7.62	7.88	7.72	7.85	10.5	10.3	11.1	11.8	7.23	8.14	7.45	9.06
		4.46		20.71	7.29	8.03	7.78	7.86	10.6	11.1	11.2	11.8	6.23	8.69	7.62	8.57
		5.94		20.71	7.38	7.69	7.65	7.67	10.5	11.4	11.7	11.9	6.25	8.11	7.35	8.88
2	Feb-20,2010	0.00	1700	20.14	7.66	7.42	7.42	7.42	12.1	12.1	12.5	13.8	6.56	6.98	7.21	6.80
		1.49		20.14	7.03	7.66	7.71	8.10	11.9	12.4	12.5	12.2	6.44	7.39	7.04	6.77
		2.97		20.14	7.39	7.65	7.49	7.62	11.9	12.1	12.7	12.4	6.68	8.10	8.08	7.93
		4.46		20.14	7.06	7.80	7.55	7.63	12.0	12.3	12.9	12.8	6.40	7.90	7.71	8.14
		5.94		20.14	7.15	7.46	7.42	7.44	12.1	12.9	12.9	13.0	6.92	8.04	8.11	6.47
3	Feb-27,2010	0.00	1700	20.29	7.85	7.78	7.83	7.85	13.1	13.1	13.5	13.8	6.79	7.40	7.75	7.39
		1.49		20.29	7.73	8.03	8.12	8.53	13.9	13.4	13.5	13.2	6.67	7.81	7.58	7.36
		2.97		20.29	7.97	8.02	7.90	8.05	13.9	13.1	13.7	13.4	6.91	8.52	8.62	8.52
		4.46		20.29	7.69	8.17	7.96	8.06	13.0	13.3	13.9	13.8	6.63	8.32	8.25	8.73
		5.94		20.29	7.21	7.83	7.83	7.87	13.1	13.9	13.9	14.0	7.15	8.46	8.65	7.06
4	Mar-12,2010	0.00	1700	21.00	7.25	7.18	7.23	7.25	12.9	13.1	13.1	13.0	6.68	7.29	7.64	7.28
		1.49		21.00	7.13	7.43	7.52	7.93	12.9	13.1	13.1	13.0	6.56	7.70	7.47	7.25
		2.97		21.00	7.37	7.42	7.30	7.45	12.9	13.1	13.1	13.0	6.80	8.41	8.51	8.41
		4.46		21.00	7.09	7.57	7.36	7.46	13.0	13.1	13.0	12.9	6.52	8.21	8.14	8.62
		5.94		21.00	6.61	7.23	7.23	7.27	12.9	13.1	13.0	12.9	7.04	8.35	8.54	8.95
5	Mar-26,2010	0.00	1700	19.50	7.04	7.03	7.02	7.04	11.8	12.0	12.0	11.9	6.57	7.18	7.53	7.17
		1.49		19.50	7.11	7.22	7.31	7.72	11.8	12.0	12.0	11.9	6.45	7.59	7.36	7.14
		2.97		19.50	7.16	7.21	7.09	7.24	11.8	12.0	12.0	11.9	6.69	8.30	8.40	8.30
		4.46		19.50	7.23	7.36	7.15	7.25	11.9	12.0	11.9	11.8	6.41	8.10	8.03	8.51
		5.94		19.50	7.05	7.02	7.02	7.06	11.8	12.0	11.9	11.8	6.93	8.24	8.43	8.84

Table-4.2 (continued): Test results- parameters measured in the field

Cell-7		Height (from bottom) (m)	Nominal Air Flow/cell (m^3/h)	Water flow/cell (ML/d)	pH				Temperature (^oC)				DO (mg/L)			
Test Number	Date				0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
6	April-16,2010	0.00	1300	20.86	1.66	7.24	7.33	7.05	17.9	17.8	18.3	18.2	1.65	4.25	3.00	3.45
		1.49		20.86	7.38	7.23	7.74	7.24	18.6	19.4	18.7	18.2	5.05	4.87	5.30	4.11
		2.97		20.86	7.04	7.22	7.26	7.23	17.1	18.0	18.3	18.1	3.87	4.89	4.88	4.98
		4.46		20.86	7.04	7.04	7.27	7.38	17.9	18.2	18.3	18.1	4.01	5.00	5.82	5.21
		5.94		20.86	7.05	7.04	7.03	7.17	17.7	18.1	18.1	18.3	4.80	4.73	4.98	4.48
7	April-30,2010	0.00	1400	20.12	6.93	6.92	6.91	6.93	18.1	18.0	18.5	18.4	1.54	4.19	2.62	3.68
		1.49		20.12	7.00	7.11	7.20	7.61	18.8	19.6	18.9	18.4	4.94	4.81	4.92	4.34
		2.97		20.12	7.05	7.10	6.98	7.13	17.3	18.2	18.5	18.3	3.76	4.83	4.50	5.21
		4.46		20.12	7.12	7.25	7.04	7.14	18.1	18.4	18.5	18.3	3.90	4.94	5.44	5.44
		5.94		20.12	6.94	6.91	6.91	6.95	17.9	18.3	18.3	18.5	4.69	4.67	4.60	4.71
8	May-14,2010	0.00	1450	19.56	7.32	7.34	7.00	7.38	18.1	18.2	17.9	18.1	6.21	6.23	5.89	5.27
		1.49		19.56	7.11	7.15	7.15	7.00	18.3	18.3	18.2	18.3	5.87	6.34	5.04	5.35
		2.97		19.56	7.22	7.27	7.30	7.78	17.9	18.4	18.2	18.1	5.11	6.76	5.19	5.67
		4.46		19.56	7.34	7.24	7.43	7.87	18.1	18.1	18.2	18.2	5.23	6.13	5.32	5.76
		5.94		19.56	7.13	7.14	7.09	7.28	18.2	18.4	17.9	18.1	6.02	6.03	5.98	6.17
9	May-21,2010	0.00	1450	19.44	6.82	6.81	6.69	6.71	18.9	18.8	19.3	19.2	2.96	4.39	3.15	4.41
		1.49		19.44	6.89	7.00	6.98	7.39	19.6	20.4	19.7	19.2	5.59	5.01	5.45	5.07
		2.97		19.44	6.94	6.88	6.76	6.91	18.1	19.0	19.3	19.1	4.41	5.03	5.03	5.94
		4.46		19.44	7.01	7.03	6.82	6.92	18.9	19.2	19.3	19.1	4.55	5.14	5.97	6.17
		5.94		19.44	6.83	6.69	6.69	6.73	18.7	19.1	19.1	19.3	5.34	4.87	5.13	5.44
10	May-28,2010	0.00	1450	20.63	6.90	6.89	6.77	6.79	20.1	21.9	21.4	21.3	2.79	4.15	4.54	5.80
		1.49		20.63	6.97	7.08	7.06	7.47	21.4	22.5	21.8	21.9	5.42	4.84	6.84	6.46
		2.97		20.63	7.02	6.96	6.84	6.99	21.6	22.9	21.9	22.2	4.24	4.76	6.42	7.33
		4.46		20.63	7.09	7.11	6.90	7.00	22.0	23.3	22.4	22.2	4.38	4.97	7.36	7.56
		5.94		20.63	6.91	6.77	6.77	6.81	22.8	23.3	22.5	22.4	5.17	4.76	6.52	6.83

Table-4.2 (continued): Test results- parameters measured in the field

Cell-7		Height (from bottom) (m)	Nominal Air Flow/cell (m^3/h)	Water flow/cell (ML/d)	pH				Temperature (°C)				DO (mg/L)			
Test Number	Date				0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
11	June-10,2010	0.00	1600	19.21	7.08	7.30	7.18	7.23	18.9	20.7	20.2	20.1	5.89	5.12	5.54	5.90
		1.49		19.21	7.15	7.49	7.47	7.91	20.2	21.3	20.6	20.7	5.92	5.44	5.72	6.23
		2.97		19.21	7.20	7.37	7.25	7.43	20.4	21.7	20.7	21.0	6.04	5.53	5.91	6.43
		4.46		19.21	7.27	7.52	7.31	7.44	20.8	22.1	21.2	21.0	6.18	5.63	6.21	6.91
		5.94		19.21	7.09	7.18	7.18	7.25	21.6	22.1	21.3	21.2	6.26	5.97	6.52	7.03
12	June-18,2010	0.00	1600	21.22	7.19	7.41	7.29	7.34	17.8	19.6	19.1	19.0	5.98	5.27	5.72	6.13
		1.49		21.22	7.26	7.60	7.48	7.42	19.1	20.2	19.5	19.6	6.01	5.59	5.90	6.46
		2.97		21.22	7.31	7.48	7.36	7.44	19.3	20.6	19.6	19.9	6.13	5.68	6.09	6.66
		4.46		21.22	7.38	7.43	7.42	7.45	19.7	21.0	20.1	19.9	6.27	5.78	6.39	7.14
		5.94		21.22	7.20	7.29	7.29	7.36	20.5	21.0	20.2	20.1	6.35	6.12	6.70	7.26
13	June-25,2010	0.00	1300	19.86	7.19	7.41	7.29	7.34	17.8	19.6	19.1	19.0	5.98	5.27	5.72	6.13
		1.49		19.86	7.26	7.60	7.48	7.42	19.1	20.2	19.5	19.6	6.01	5.59	5.90	6.46
		2.97		19.86	7.31	7.48	7.36	7.44	19.3	20.6	19.6	19.9	6.13	5.68	6.09	6.66
		4.46		19.86	7.38	7.43	7.42	7.45	19.7	21.0	20.1	19.9	6.27	5.78	6.39	7.14
		5.94		19.86	7.20	7.29	7.29	7.36	20.5	21.0	20.2	20.1	6.35	6.12	6.70	7.26
14	July-20,2010	0.00	1600	20.00	7.35	7.49	7.58	7.30	23.9	24.1	24.4	24.8	4.56	4.39	4.23	4.45
		1.49		20.00	7.38	7.48	7.49	7.49	23.5	24.6	24.5	24.9	5.25	4.67	4.39	4.76
		2.97		20.00	7.29	7.47	7.51	7.48	23.1	24.5	24.6	24.8	4.67	4.89	4.88	4.98
		4.46		20.00	7.29	7.29	7.52	7.63	24.3	24.5	24.7	24.9	4.36	5.14	5.27	5.21
		5.94		20.00	7.30	7.29	7.28	7.42	24.3	24.4	24.6	24.9	4.43	5.73	5.82	5.37
15	July-23,2010	0.00	1300	19.45	7.42	7.53	7.68	7.82	21.8	22.6	22.1	22.0	6.09	5.59	6.04	6.24
		1.49		19.45	7.49	7.72	7.87	7.90	22.1	22.2	22.5	22.6	6.12	5.91	6.22	6.57
		2.97		19.45	7.54	7.60	7.75	7.92	22.3	22.6	22.6	22.9	6.24	6.00	6.41	6.77
		4.46		19.45	7.61	7.55	7.81	7.93	22.7	22.0	22.1	21.9	6.38	6.10	6.71	7.25
		5.94		19.45	7.43	7.41	7.68	7.84	22.5	22.0	22.2	22.1	6.46	6.44	7.02	7.37

Table-4.2 (continued): Test results- parameters measured in the field

Cell-7		Height (from bottom) (m)	Nominal Air Flow/cell (m^3/h)	Water flow/cell (ML/d)	pH				Temperature (^oC)				DO (mg/L)			
Test Number	Date				0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
16	July-30,2010	0.00	1300	21.22	7.30	7.41	7.56	7.70	22.9	23.7	23.2	23.1	4.94	5.45	5.90	6.10
		1.49		21.22	7.37	7.60	7.75	7.78	23.2	23.3	23.6	23.7	4.97	5.77	6.08	6.43
		2.97		21.22	7.42	7.48	7.63	7.80	23.4	23.7	23.7	24.0	5.09	5.86	6.27	6.63
		4.46		21.22	7.49	7.43	7.69	7.81	23.8	23.1	23.2	23.0	5.23	5.96	6.57	7.11
		5.94		21.22	7.31	7.29	7.56	7.72	23.6	23.1	23.3	23.2	5.31	6.30	6.88	7.23

Table-4.3: Test results- parameters measured in the laboratory

Cell-7		Height (from bottom) (m)	NH_3-N (mg/L)				NO_3-N (mg/L)				COD (mg/L)				BOD_5 -calculated (mg/L)			
Test Number	Date		0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
1	Feb-14-2010	0.00	2.0	5.1	4.9	6.2	0.6	0.7	0.8	0.8	120	203	208	200	21	36	37	35
		1.49	1.7	4.4	4.4	4.8	0.9	0.7	1.0	0.9	98	80	74	40	17	14	13	7
		2.97	1.5	3.9	3.5	4.2	0.7	0.9	1.2	1.2	97	40	51	34	17	7	9	6
		4.46	1.7	3.2	3.3	3.2	1.3	1.0	1.8	1.8	96	24	19	23	17	4	3	4
		5.94	1.4	2.5	2.1	3.0	0.6	0.6	0.6	1.0	84	17	21	18	15	3	4	3
2	Feb-20,2010	0.00	3.1	8.3	6.6	9.0	0.6	0.6	0.6	0.6	111	266	252	224	20	47	45	40
		1.49	2.3	5.0	4.1	5.6	0.7	0.6	0.8	0.9	109	73	63	50	19	13	11	9
		2.97	6.8	4.1	3.2	5.0	1.3	1.3	0.7	1.0	111	51	46	35	20	9	8	6
		4.46	4.9	3.9	3.0	2.8	0.8	1.1	0.6	1.4	111	52	32	50	20	9	6	9
		5.94	3.4	2.9	2.5	2.3	0.7	1.1	1.9	2.0	107	39	25	30	19	7	4	5
3	Feb-27,2010	0.00	3.5	10.8	9.7	15.0	0.6	0.6	0.6	0.6	129	208	211	226	23	37	37	40
		1.49	2.6	6.5	6.1	9.4	0.7	0.6	0.8	0.9	117	91	99	93	21	16	18	17
		2.97	3.5	5.3	4.8	8.4	1.3	1.3	0.7	1.0	118	74	68	57	21	13	12	10
		4.46	5.5	5.1	4.4	4.6	0.8	1.1	0.6	1.4	109	65	61	44	19	11	11	8
		5.94	3.8	3.8	3.8	4.4	0.7	1.1	1.8	1.9	144	49	38	28	26	9	7	5
4	Mar-12,2010	0.00	3.3	10.1	13.6	14.1	0.7	0.7	0.7	0.7	142	221	224	240	25	39	40	42
		1.49	2.4	6.1	5.7	8.8	0.8	0.7	0.8	1.0	130	105	112	107	23	19	20	19
		2.97	3.3	5.0	4.5	7.9	1.4	1.4	0.8	1.1	132	88	81	70	23	16	14	12
		4.46	5.2	4.8	4.2	4.4	0.9	1.2	0.7	1.5	122	78	74	47	22	14	13	8
		5.94	3.6	3.5	3.5	4.0	0.8	1.2	2.1	2.2	158	63	51	42	28	11	9	7
5	Mar-26,2010	0.00	4.6	13.7	18.1	18.9	0.9	0.8	0.8	0.8	152	215	217	229	27	38	38	41
		1.49	3.4	8.3	7.8	11.9	0.9	0.9	1.0	1.1	142	122	128	124	25	22	23	22
		2.97	4.6	6.9	6.2	10.7	1.5	1.5	0.9	1.2	144	109	104	95	25	19	18	17
		4.46	7.1	6.6	5.8	6.0	1.0	1.3	0.8	1.5	136	101	98	100	24	18	17	18
		5.94	5.0	4.9	4.9	5.7	0.9	1.3	2.0	2.0	164	89	80	72	29	16	14	13

Table-4.3 (continued): Test results- parameters measured in the laboratory

Cell-7		Height (from bottom) (m)	NH_3-N (mg/L)				NO_3-N (mg/L)				COD (mg/L)				BOD_5 -calculated (mg/L)			
Test Number	Date		0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
6	April-16,2010	0.00	6.6	11.3	13.8	14.2	0.9	0.9	0.9	0.9	216	232	219	228	38	41	39	40
		1.49	3.8	6.9	8.7	6.4	1.0	0.9	1.1	1.1	204	177	194	186	36	31	34	33
		2.97	4.4	3.2	4.1	4.5	1.6	1.5	1.0	1.3	223	136	146	123	39	24	26	22
		4.46	9.0	2.8	2.6	3.4	1.1	1.3	0.9	1.6	211	88	104	64	37	16	18	11
		5.94	5.9	2.5	2.6	3.1	1.0	1.4	2.1	2.1	159	36	29	27	28	6	5	5
7	April-30,2010	0.00	5.8	9.3	11.1	11.4	1.0	1.0	1.0	1.0	194	207	197	204	34	37	35	36
		1.49	4.9	8.4	10.4	7.9	1.1	1.0	1.2	1.2	184	162	176	169	33	29	31	30
		2.97	5.6	4.2	5.3	5.7	1.7	1.6	1.1	1.4	200	128	136	117	35	23	24	21
		4.46	7.6	2.6	2.5	3.2	1.2	1.4	1.0	1.7	190	88	101	68	34	16	18	12
		5.94	5.2	2.4	2.5	2.9	1.1	1.5	2.2	2.2	147	45	38	37	26	8	7	7
8	May-14,2010	0.00	5.7	9.0	10.6	10.5	0.8	0.8	0.8	0.8	129	144	132	140	23	26	23	25
		1.49	3.2	5.5	6.6	4.7	0.9	0.8	1.0	0.7	118	93	109	101	21	17	19	18
		2.97	3.8	2.5	3.1	3.2	1.0	1.0	0.9	0.8	136	55	65	43	24	10	11	8
		4.46	7.8	2.2	1.9	2.5	1.0	0.9	0.8	1.0	125	47	25	32	22	8	4	6
		5.94	5.1	1.9	1.9	2.3	0.9	0.9	1.4	1.4	76	14	15	21	14	3	3	4
9	May-21,2010	0.00	5.3	8.8	10.7	11.0	0.9	0.8	0.9	0.8	185	198	188	195	33	35	33	35
		1.49	4.5	7.9	9.9	7.4	0.9	0.9	1.0	1.1	176	155	168	161	31	27	30	29
		2.97	5.2	3.8	4.8	5.2	1.5	1.4	1.0	1.2	191	122	130	111	34	22	23	20
		4.46	7.1	2.3	2.2	2.8	1.0	1.3	0.9	1.5	182	77	77	45	32	14	14	8
		5.94	4.7	2.0	2.1	2.6	0.9	1.3	1.9	1.9	140	29	24	22	25	5	4	4
10	May-28,2010	0.00	7.8	12.6	14.3	13.3	0.8	0.7	0.7	0.7	180	186	199	225	32	33	35	40
		1.49	6.5	11.3	13.2	8.9	0.8	0.7	0.8	0.9	169	135	176	215	30	24	31	38
		2.97	7.5	5.2	6.2	6.2	1.3	1.2	0.8	1.0	186	97	132	176	33	17	23	31
		4.46	10.5	3.1	2.7	3.2	0.9	1.1	0.7	1.2	176	45	70	117	31	8	12	21
		5.94	6.9	2.7	2.6	2.9	0.8	1.1	1.6	1.5	127	26	7	40	23	5	1	7

Table-4.3 (continued): Test results- parameters measured in the laboratory

Cell-7		Height (from bottom) (m)	NH_3-N (mg/L)				NO_3-N (mg/L)				COD (mg/L)				BOD_5 -calculated (mg/L)			
Test Number	Date		0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min	0 min	30 min	60 min	120 min
11	June-10,2010	0.00	12.5	13.7	15.2	13.1	0.8	0.8	0.8	0.7	182	183	200	225	32	32	35	40
		1.49	11.5	11.5	13.3	10.7	1.2	1.1	1.2	1.3	165	136	122	146	29	24	22	26
		2.97	11.2	5.0	7.5	6.3	1.9	1.8	1.6	1.4	181	100	102	110	32	18	18	19
		4.46	10.8	2.2	2.9	2.7	2.5	2.2	2.0	1.8	171	51	79	55	30	9	14	10
		5.94	12.0	2.0	2.0	1.8	1.7	2.2	2.3	2.3	126	34	21	53	22	6	4	9
12	June-18,2010	0.00	9.1	8.8	9.0	7.7	0.9	0.9	0.9	0.8	216	218	237	264	38	39	42	47
		1.49	8.4	7.4	7.9	6.3	1.3	1.2	1.4	1.4	198	166	151	178	35	29	27	31
		2.97	8.1	3.2	4.4	3.7	2.1	2.0	1.8	1.6	216	127	129	138	38	22	23	24
		4.46	7.9	1.4	1.7	1.6	2.7	2.4	2.2	2.0	204	73	104	78	36	13	18	14
		5.94	8.7	1.2	1.2	1.3	1.8	2.4	2.6	2.5	155	54	40	75	27	10	7	13
13	June-25,2010	0.00	9.1	8.8	9.0	7.7	0.9	0.9	0.9	0.8	216	218	237	264	38	39	42	47
		1.49	8.4	7.4	7.9	6.3	1.3	1.2	1.4	1.4	198	166	151	178	35	29	27	31
		2.97	8.1	3.2	4.4	3.7	2.1	2.0	1.8	1.6	216	127	129	138	38	22	23	24
		4.46	7.9	1.4	1.7	1.6	2.7	2.4	2.2	2.0	204	73	104	78	36	13	18	14
		5.94	8.7	1.2	1.2	1.3	1.8	2.4	2.6	2.5	155	54	40	25	27	10	7	4
14	July-20,2010	0.00	5.7	11.0	14.2	14.6	0.8	0.8	1.0	0.9	225	240	228	237	40	43	40	42
		1.49	3.2	6.7	8.9	6.6	0.9	0.8	1.1	1.2	214	188	204	196	38	33	36	35
		2.97	3.8	3.1	4.2	4.5	1.4	1.5	1.1	1.4	232	149	159	136	41	26	28	24
		4.46	7.8	2.7	2.6	3.5	1.0	1.3	1.0	1.7	221	103	118	80	39	18	21	14
		5.94	5.1	2.4	2.6	3.2	0.9	1.3	2.2	2.3	171	54	47	45	30	10	8	8
15	July-23,2010	0.00	8.4	7.5	6.8	5.9	0.8	0.7	0.7	0.6	184	186	203	229	33	33	36	41
		1.49	7.8	6.3	6.0	4.8	1.1	1.0	1.1	1.0	166	136	122	147	29	24	22	26
		2.97	7.5	2.7	3.4	2.8	1.8	1.6	1.4	1.1	183	99	101	109	32	17	18	19
		4.46	7.3	1.2	1.3	1.2	2.4	2.0	1.8	1.4	173	48	77	52	31	8	14	9
		5.94	8.1	1.2	1.2	1.2	1.6	2.0	2.1	1.9	126	30	16	29	22	5	3	5

Table-4.3 (continued): Test results- parameters measured in the laboratory

Cell-7		Height (from bottom) (m)	NH_3-N (mg/L)				NO_3-N (mg/L)				COD (mg/L)				BOD_5 -calculated (mg/L)			
Test Number	**Date**		**0 min**	**30 min**	**60 min**	**120 min**	**0 min**	**30 min**	**60 min**	**120 min**	**0 min**	**30 min**	**60 min**	**120 min**	**0 min**	**30 min**	**60 min**	**120 min**
16	July-30,2010	0.00	8.9	7.9	7.1	6.1	0.8	0.7	0.7	0.6	190	192	211	239	34	34	37	42
		1.49	8.2	6.6	6.3	5.0	1.2	1.0	1.1	1.0	171	139	124	151	30	25	22	27
		2.97	7.9	2.8	3.5	2.9	1.9	1.7	1.5	1.2	190	99	101	110	34	17	18	19
		4.46	7.7	1.3	1.4	1.3	2.6	2.1	1.9	1.5	178	44	75	48	32	8	13	9
		5.94	8.5	1.2	1.2	1.2	1.7	2.1	2.2	2.0	127	24	9	25	23	4	2	4

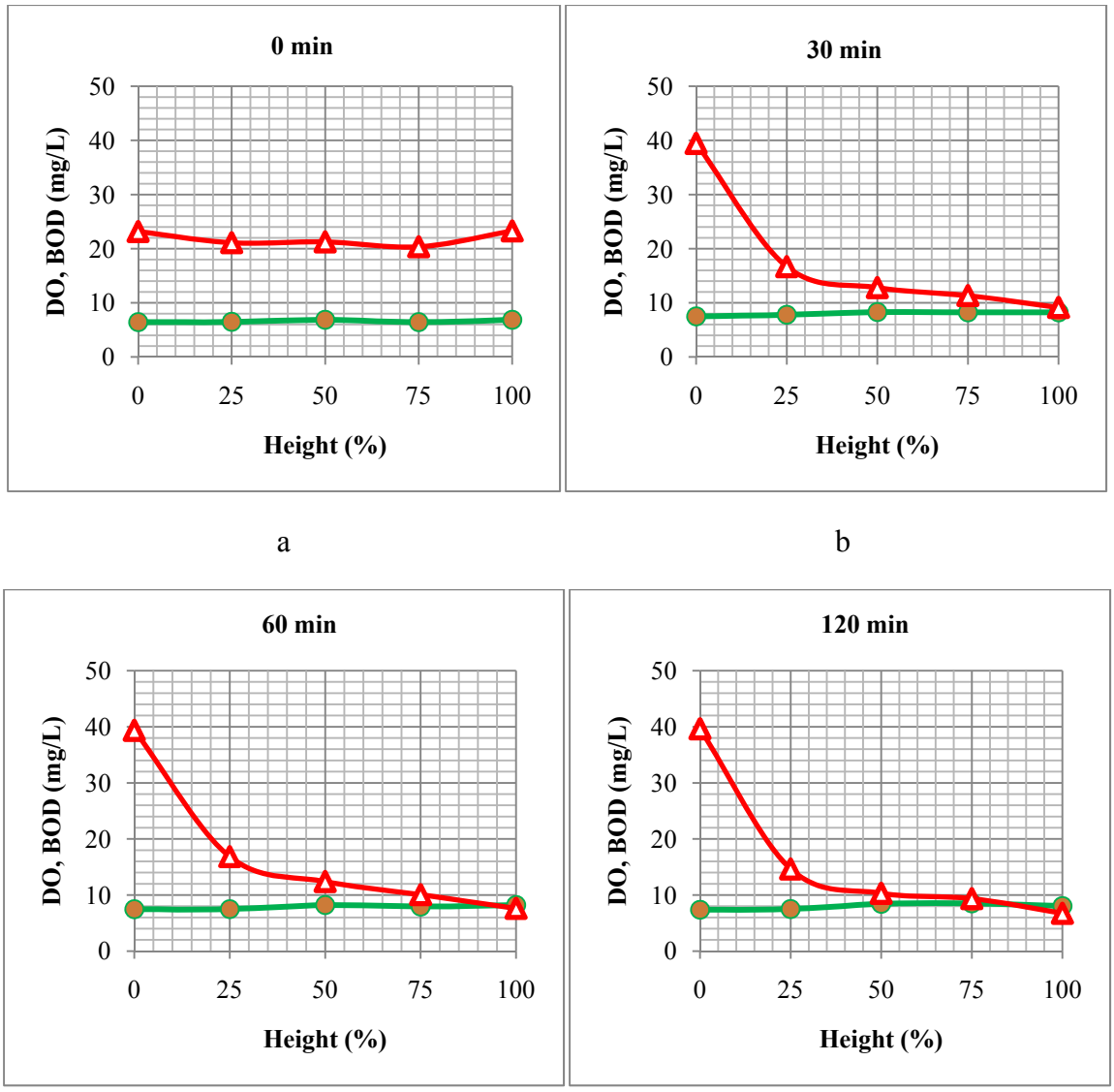


Figure 4.1: BOD profile (triangles) and DO profile (circles) in cell # 7 at 1700 m^3 /h nominal air flow rate at a) 0 min., b) 30 min., c) 60 min., d) 120 min

Figure 4.2 shows that in the filtration mode at an airflow rate of 1300 m^3/h the BOD concentration decreased at a constant rate throughout the cell in contrast to 1700m^3/h (Figure 4.1), where the decreased in BOD in the cell was mainly in the first quarter. Because of the lower oxygen input, the biomass probably oxidized the organic matter at a lower rate. In fact the rate of BOD oxidation may be limited by the available oxygen, (as opposed to organic matter) leading to a constant rate of oxidation throughout the depth of the cell.

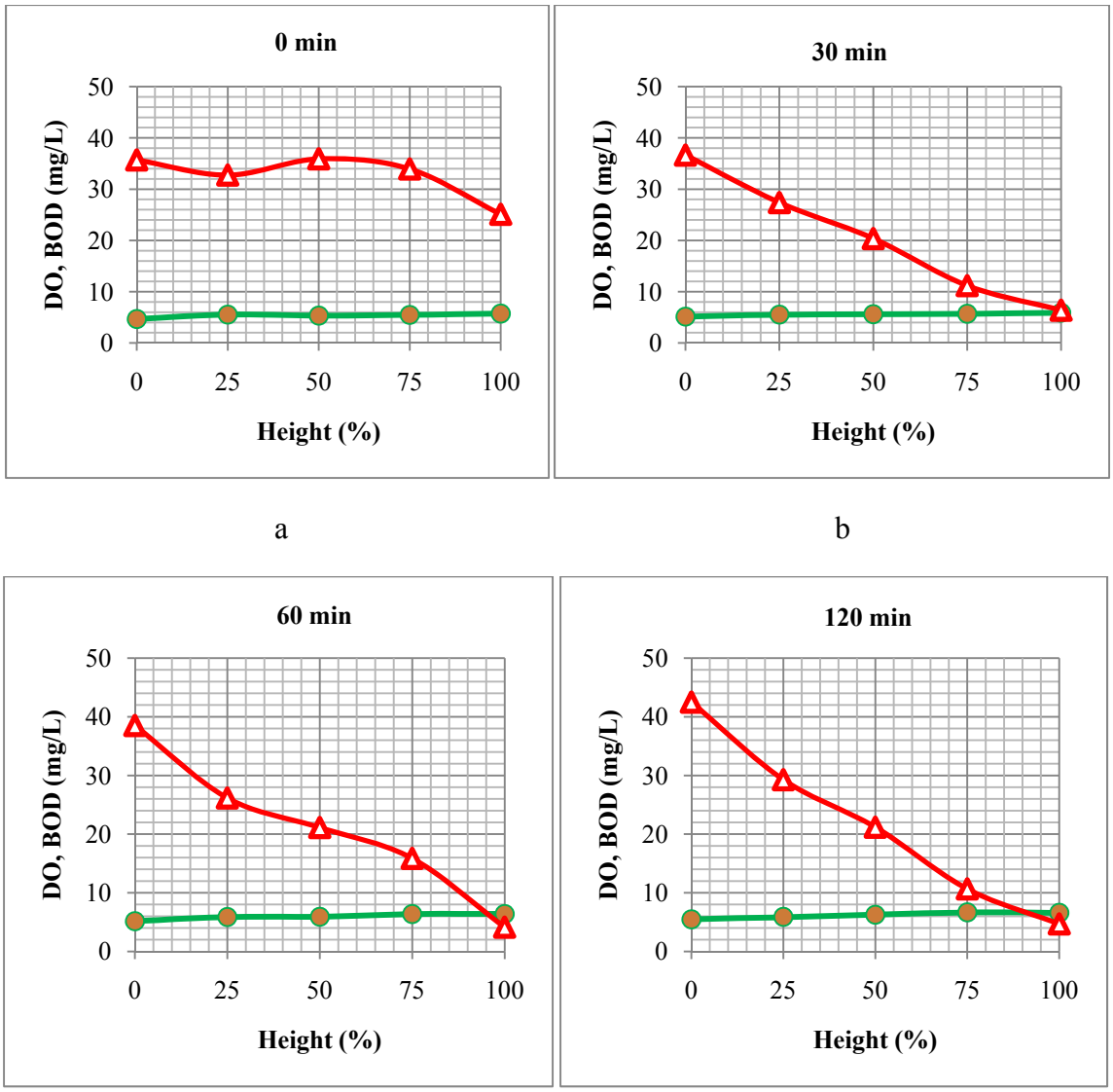


Figure 4.2: BOD profile (triangles) and DO profile (circles) in cell # 7 at 1300 m^3/h nominal air flow rate at a) 0 min, b) 30 min, c) 60 min, d) 120 min

Figure 4.3 compares BOD profiles at 120 min for various airflow rates. Profiles at 120 minutes are shown because they more closely resemble the steady-state filter condition which occurred during the bulk of the filter runtime.

The average inflow BOD_5 for the BAF was 40 mg/L whereas the outflow BOD_5 was around 7 mg/L after 120 minutes during the filtration, regardless of the airflow rate. This shows that the cells were removing 88 % of the BOD, independent of nominal airflow. A characteristic change in removal of BOD with respect to the depth of the cell was

expected and demonstrated by the tests. For the 1700 m^3/h nominal air flow rate, 75 % of the BOD was removed within the 1st 50 % of the cell and the overall removal efficiency was 82.5 %. With the decrease of nominal air flow rate to 1300 m^3/h this characteristic had changed and around 70 % removal efficiency was achieved within the first 50 % of the cell. For 1600 m^3/h and 1450 m^3/h nominal flow an average of 80 % and 82.5 % removal efficiency were achieved respectfully. For the lowest nominal airflow of 1300 m^3/h, around 88.5 % removal efficiency was found and this is interestingly higher than at the highest amount of nominal airflow in the cell.

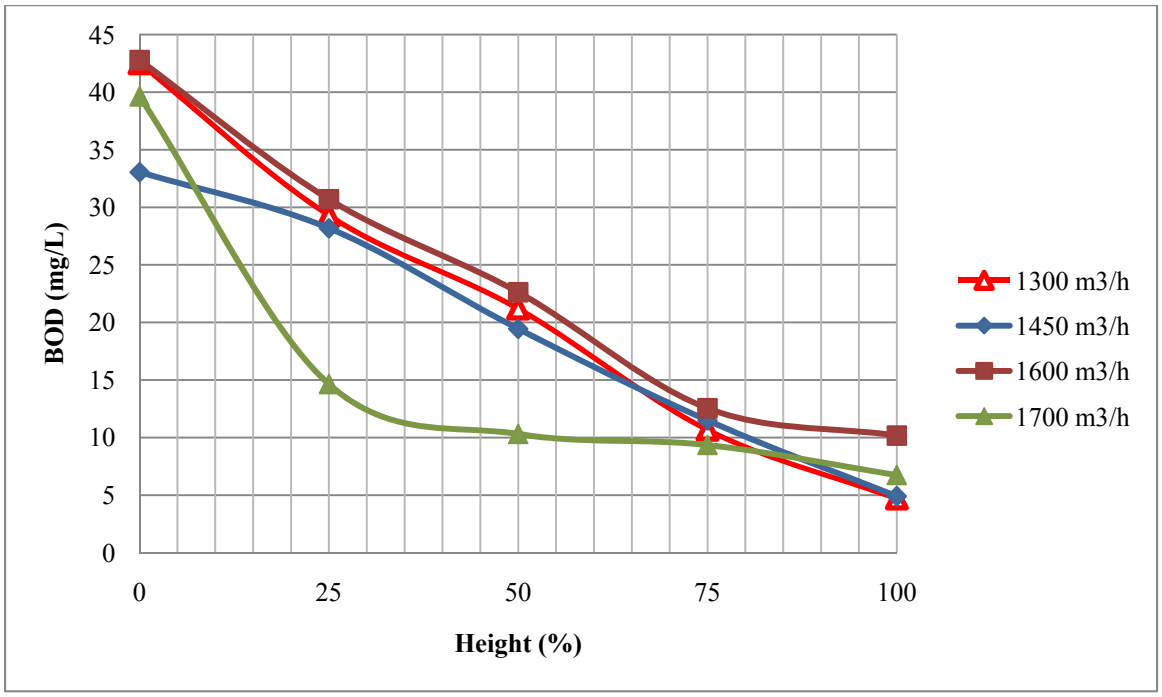


Figure 4.3: Average BOD profile in cell # 7 at different nominal air flow rates at 120 minutes after startup

4.3.2 N change in cell

Figures 4.4 and 4.5 show the nitrogen profiles in the BAF cell at high and low airflow rates, respectfully. After the start of filtration (after 0 minute), there is a decrease in NH_4^+ and increase in NO_3^- throughout the cell. In most cases ammonium nitrogen removal is essentially complete (up to required effluent compliance limit 2.2 mg/L) by the 75 %

height of the cell. At times less than 120 minutes, the greatest nitrification took place in the first 25 % of the cell.

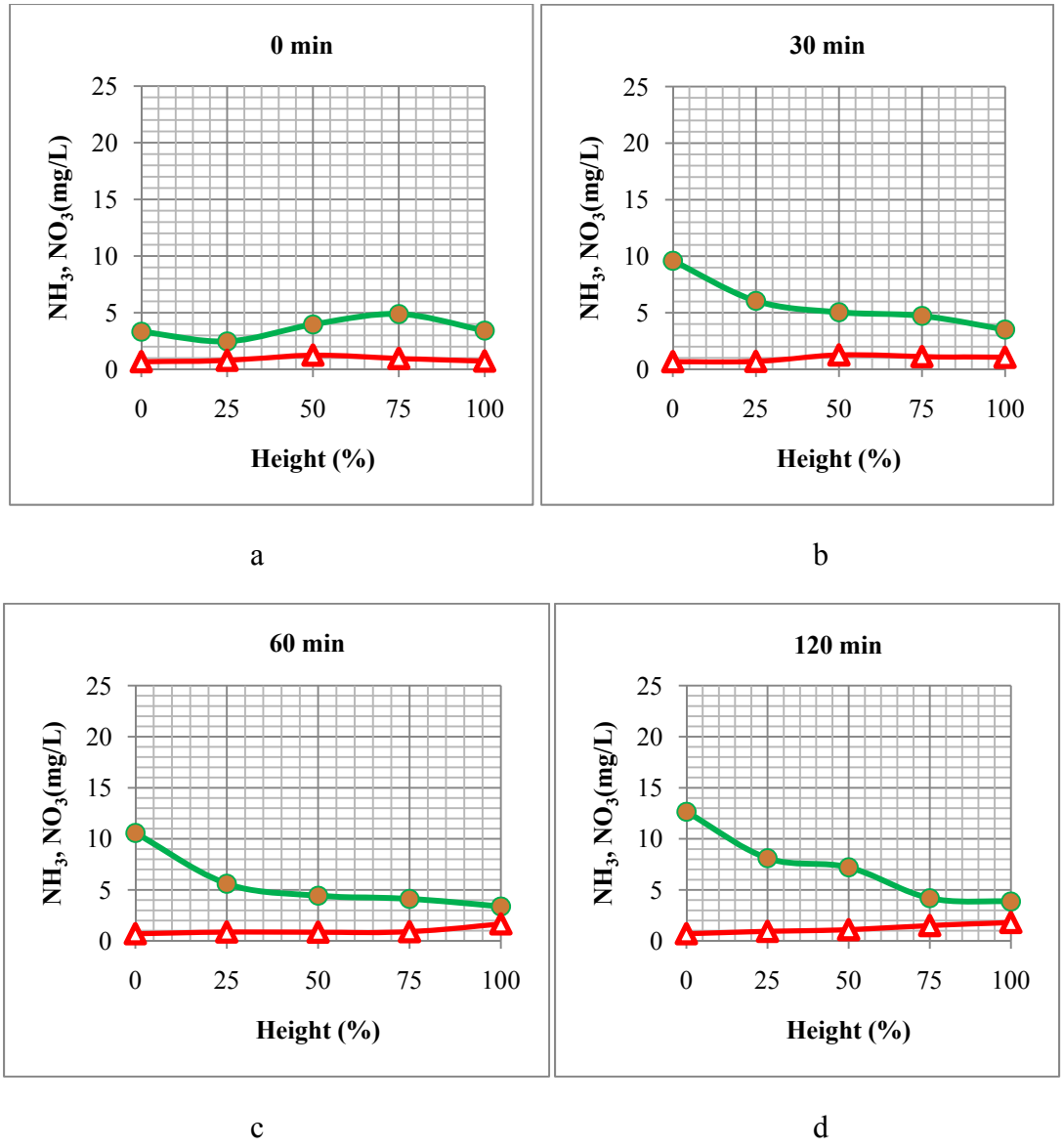


Figure 4.4: NH_3 (circles) and NO_3^- (triangles) change in cell # 7 at 1700 m^3/h nominal air flow rates at a) 0 min., b) 30 min., c) 60 min., d) 120 min

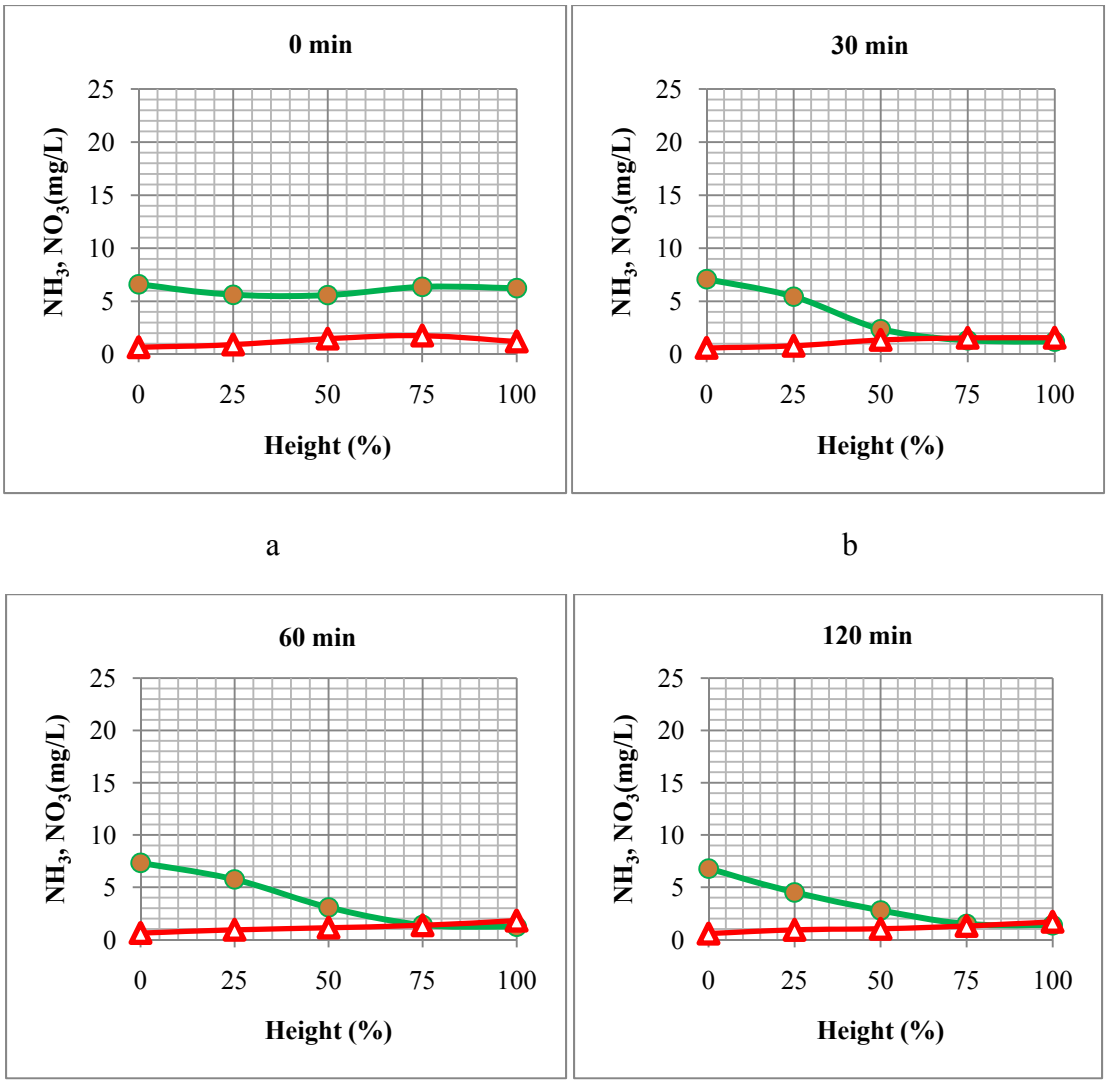


Figure 4.5: NH_3 (circles) and NO_3^- (triangles) change in cell # 7 at 1300 m^3/h nominal air flow rate at a) 0 min., b) 30 min., c) 60 min., d) 120 min.

Figure 4.6 compares the total ammonia profile at 120 minutes for various aeration levels. Again 120 minutes was chosen because it was closer to the steady state filtration condition. The average inflow NH_4^+ for the BAF is 11 mg/L whereas the outflow was around 2.5 mg/L after 120 minutes of filtration. This indicates that the cells were effective in NH_4^+ removal and it was independent of nominal airflow rate. In all the cases, around 83.3 % NH_4^+ removal efficiency was achieved. There was no characteristic change in removal of NH_4^+ in respect to the depth of the cell. For 1700 m^3/h nominal air

flow rate, 58 % NH_4^+ was removed within the 50 % of the cell height whereas the overall removal efficiency was 89 %. For 1600 m^3/h and 1450 m^3/h nominal airflow rates, an average of 83.3 % removal efficiency was achieved. For the lowest nominal airflow of 1300 m^3/h, around 82.3 % removal efficiency was achieved, with 58 % removal occurring in the first half of the cell.

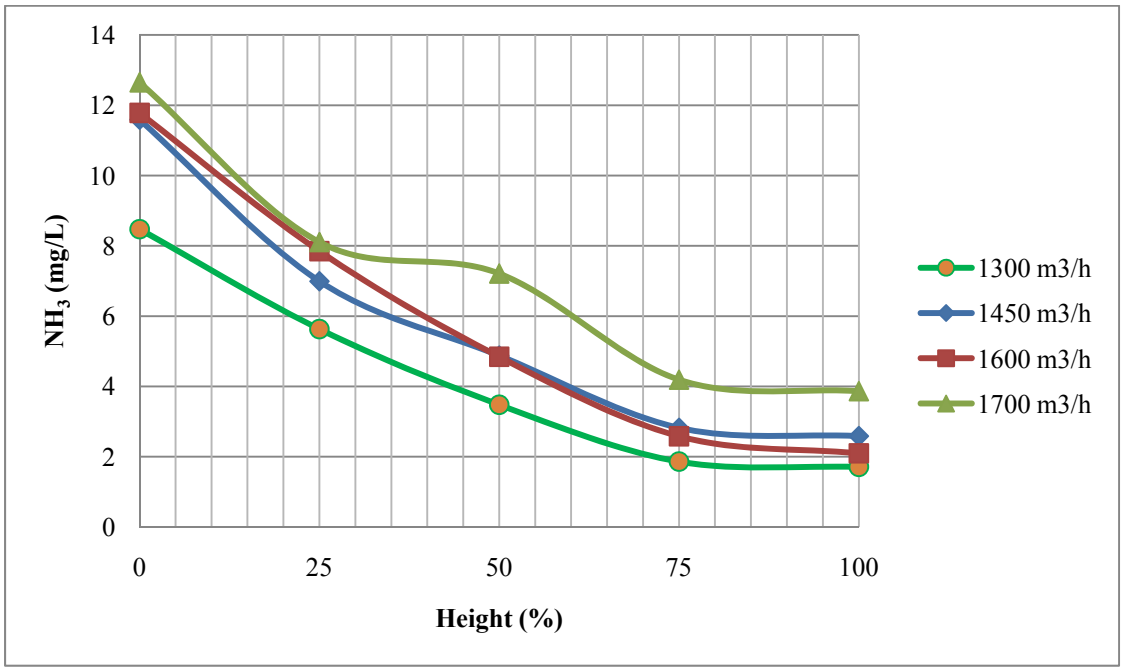


Figure 4.6: Average total NH_3 profiles in cell # 7 at different nominal air flow rates at 120 min after startup

For LRWRP, the compliance limit for unionized ammonia is 0.1 mg/L (CH2M Gore and Storrie Ltd., 1996). Considering the worst case scenario, temperature (25°C) and pH (8.0), the ratio of unionized to total ammonia is 1:12.5 (Thomann and Mueller, 1987). So the compliance limit should be around 2.2 mg/L for total NH_3. The system is in the range of the compliance limit even at the lower aeration rate.

Figure 4.7 shows the profiles of nitrate in the BAF under varying airflow rates at 120 minutes. There is no trend with respect to the change of the profile as aeration is

increased. Average BAF influent NO_3^- is 0.8 mg-N/L which increases to 2 mg/L in the effluent. There is no trend for the total nitrate produced as a function of aeration.

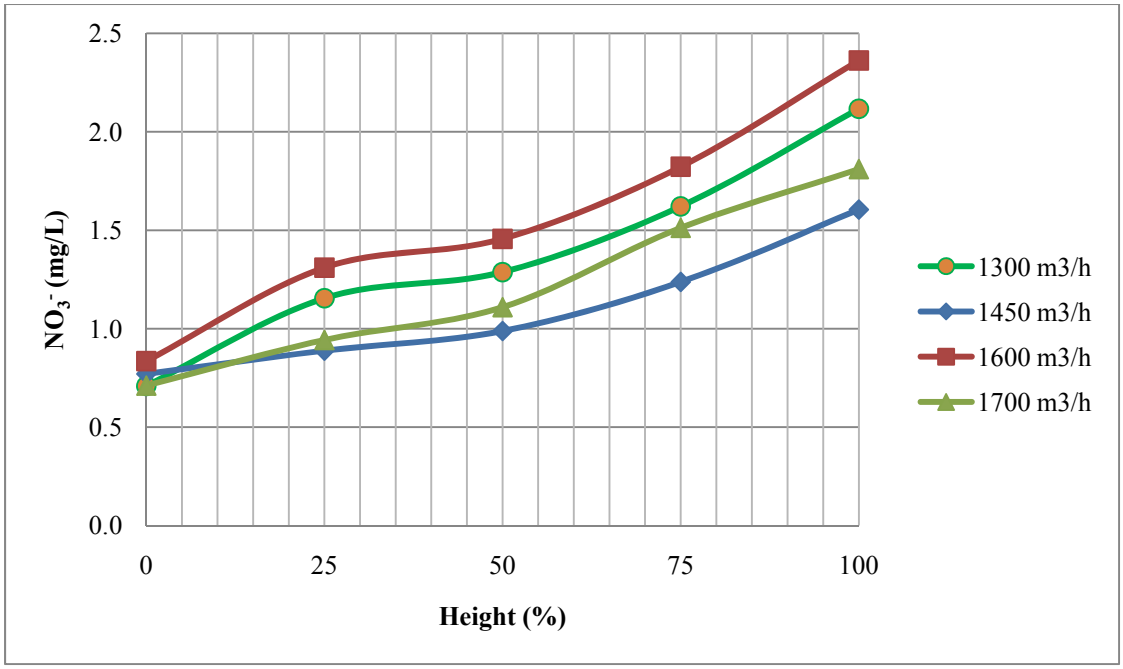


Figure 4.7: Average NO_3^- profile in cell # 7 at different nominal air flow rates at 120 minutes after startup

4.4 Discussions

4.4.1 Fate of NH_4^+

Removal of NH_4^+ is one of the important regulatory criteria for LRWRP. This is achieved by two ways. First the carbonaceous bacteria use a small portion as a nutrient source. If a plant has a large number of filamentous bacteria, this value will be lower. Some filamentous bacteria grow quite well in a nutrient deficient environment and do not consume nutrients quite the same as the floc forming bacteria (Gerardi, 2006). The second way to remove ammonia is through nitrification. In a BAF, nitrification is the primary method to remove ammonia from wastewater. Nitrification is a process where ionized ammonia (NH_4^+) is oxidized into NO_2^- and NO_2^- is oxidized to NO_3^- in water. There should be a balance in the total N in the system, for this process.

In LRWRP, the BAF characteristics shows that this balance is not achieved when one considers only nitrification. On average, the NH_4^+ decrease in the BAF was 10 mg-N/L whereas the effluent NO_3^- was only 1.2 mg/L-N higher than the influent. This means nitrification can only account for 12 % of ammonia loss. The loss of the other 88 % is not taken into account. This is very unusual and indicates that NH_4^+ was being converted to other forms rather than NO_3^- and/or the system was loosing nitrogen in some other way.

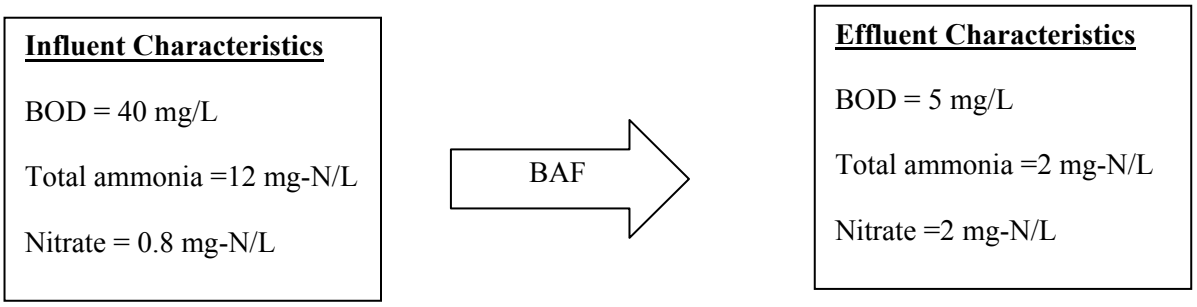


Figure 4.8: Influent and effluent characteristics of BAF

The possible causes for this nitrogen imbalance were analyzed.

The first possible cause may be that NH_4^+ was being stripped out from the cell due to aeration. The worst case scenario was assumed and the total amount of ammonia stripped per day was calculated. The assumptions were:

- Total influent ammonia was NH_3.
- All the air bubbles were saturated with NH_3 when they left the BAF.
- Water temperature was 20^{o}C.

Average NH_3 inflow =12 mg/L

Average water flow rate per cell =21 ML/d

Maximum nominal airflow =1700 m^3/h

Loading of ammonia = 21 ML/d x 12 NH_4^+-N mg/L

$= 21 \times 10^6$ L/d x 12×10^{-3} NH_4^+-N g/L

$= 252000$ NH_4^+-N g/d

Average NH_3 inflow = 12 mg/L-N

$$= \frac{17 \text{ mg } NH_3}{14 \text{mgN}} \times 12 \text{ mg /L-}NH_3$$

$$= 14.6 \text{ mg /L -}NH_3$$

Mass of NH_3 per 100 masses of H_2O = $\frac{14.6}{10000} \frac{\text{mg NH3}}{100\text{mg H2O}}$

$$= 1.46 \times 10^{-3}$$

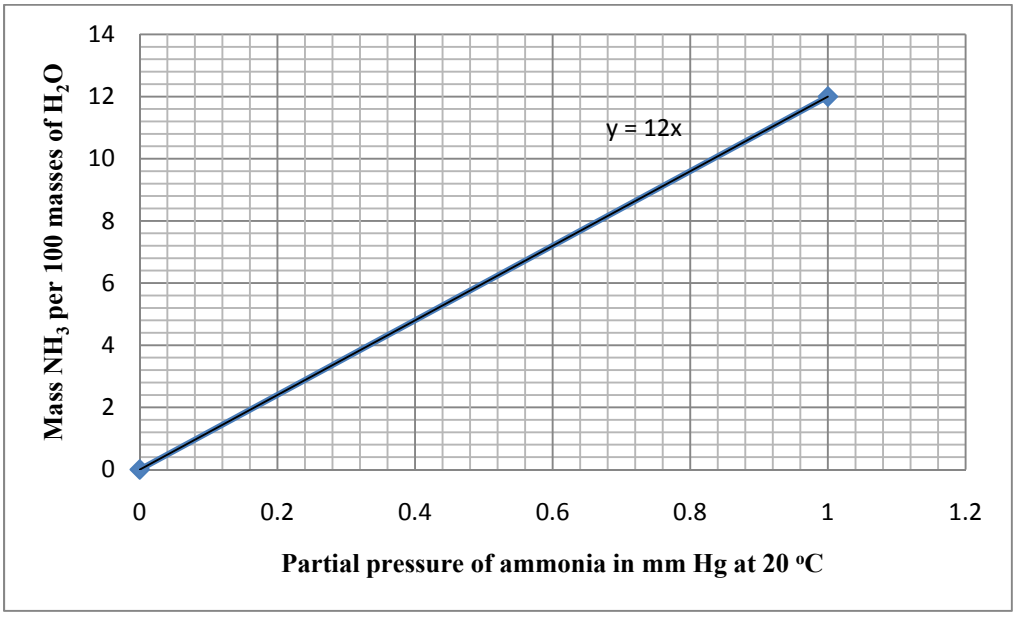


Figure 4.9: NH_3 Solubility in water (Adopted from Cooper and Alley, 1994)

So, the partial pressure of NH_3(mm Hg) at 20°C is (Figure-4.9) = $\frac{1.46 \times 10^{-3}}{\frac{12}{mm\ Hg}}$

$$= 1.216 \times 10^{-4} \text{ mm Hg}$$

From the ideal gas law, PV=nRT [4.3]

Therefore, $$n = \frac{PV}{RT} = \frac{\frac{1.216 \times 10^{-4}\ \text{mm Hg}}{760\ \frac{\text{mmHg}}{\text{atm.}}} \times 1700\ \text{m3/h} \times 1000\ \frac{\text{L}}{\text{m3}}}{0.8205\ \frac{\text{atm. L}}{\text{mole K}} \times 293\ \text{K}} = 1.13 \times 10^{-2}\ \text{mol/h}$$

$$m = nMW = 1.13 \times 10^{-2}\ \text{mol/h} \times 14\ \text{g/mole} = 0.158\ NH_4^+\text{-N g/h}$$

Loss of ammonia = 0.158 NH_4^+-N g/h = 3.80 g/d

Thus, under the worst condition the total loss of ammonia would be $= \frac{3.80\ \text{g/d} \times 100\ \%}{252000\text{g/d}}$

$= 1.51 \times 10^{-3}\ \%$

This is very low as compared to the total NH_4^+ loading and thus negligible. Therefore, ammonia stripping would not be the main reason for the loss of 88 % of ammonia.

The second possible cause may be the presence of a high amount of suspended solids in the influent samples. If ammonia is attached to the solids, filtration in the BAF, which removes the suspended solids, would also remove a significant amount of ammonia without producing nitrates. On two different days, centrifuging (15 minutes, 3500 rpm) was performed to remove the suspended solids from the samples (Table 4.4) to see if SS made a difference in the N balance.

Table 4.4: Ammonia nitrogen measurement before and after the SS were separated by centrifuging for tests #12 and #13

Test Number	Date	Total NH_3-N(mg/L)-before centrifuging				Total NH_3-N(mg/L)-in supernatant after centrifuging			
		0 min.	30 min.	60 min.	120 min.	0 min.	30 min.	60 min.	120 min.
12	June-18,2010	12.6	13.7	15.3	13.1	12.5	13.7	15.2	13.1
		11.5	12.1	13.4	10.8	11.5	11.5	13.3	10.7
		11.3	5.0	7.5	6.3	11.2	5.0	7.5	6.3
		10.8	2.2	2.9	2.7	10.8	2.2	2.9	2.7
		12.0	2.0	2.0	1.9	12.0	2.0	2.0	1.8
14	July-20,2010	9.1	8.9	9.0	7.7	9.1	8.8	9.0	7.7
		8.4	7.4	7.9	6.3	8.4	7.4	7.9	6.3
		8.1	3.3	4.4	3.7	8.1	3.2	4.4	3.7
		7.9	1.5	1.7	1.6	7.9	1.4	1.7	1.6
		8.7	1.2	1.2	1.3	8.7	1.2	1.2	1.3

No significant change in NH_4^+-N concentration was found between before and after the suspended solids was removed. Therefore, not a significant amount of NH_3 was associated with SS.

The LRWRP 2009 plant data for Total Kjeldahl N, N_{org} (calculated from TKN minus NH_3), NH_3 and NO_3 is summarized in Figure 4.10 and the same trend of unbalanced –N is found in the system. For 2009 the average influent NH_4^+ was 10.19 mg/L whereas effluent was 4.56 mg/L and influent NO_3 was 1.03 mg/L; whereas the effluent was 3.73 mg/L; and influent NO_3^- was 1.03 mg/L. Clearly, the change in NH_3 was greater than the change in NO_3^- due to nitrification. LRWRP has been testing (NO_3^- +NO_2^-) after removal of suspended solids and their results show the same trend as these. Therefore, this is unlikely to be the cause for such a high loss of NH_3-N in the system.

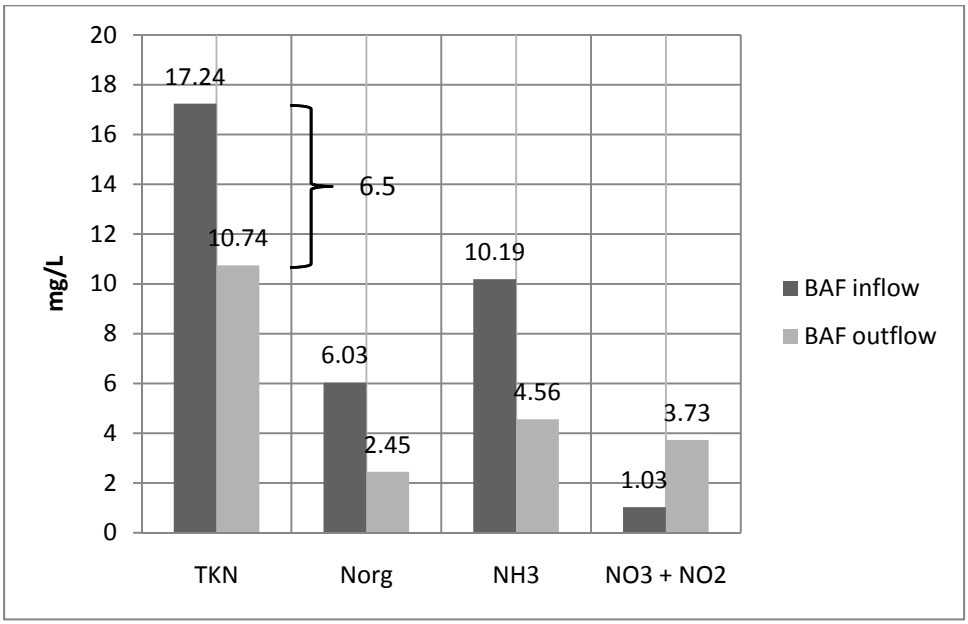


Figure 4.10: Average nitrogen level on BAF (adapted from LRWRP lab data)

The third possible cause is that NH_3 was being converted to NO_2^-, and NO_2^- and not to NO_3^-. This is unlikely to happen in the BAF as the DO was always higher than 5.0 mg/L due to high aeration in the system. So enough oxygen was always present to convert NO_2^- to NO_3^-. In addition, LRWRP measured NO_2^- +NO_3^- in their analysis (Figure 4.10) and the imbalance existed even though NO_2^- was taken into account.

The fourth possible cause is that NH_4^+ is being converted to soluble N_{org} which is quite unlikely in a biological aerated filtration system. Figure 4.10 also indicates a reduction in organic nitrogen in the system. So production of N_{org} should not be the possible cause of loosing ammonia nitrogen.

The fifth possible cause is that NO_3^- was converted to $N_{2(g)}$ (de-nitrification). Denitrification is the use of nitrate or nitrite by facultative anaerobic bacteria for the degradation of soluble CBOD (Gerardi, 2006).

$$6NO_3^- + 5CH_3OH \xrightarrow{\text{Facultative anaerobic bacteria}} 3N_2 + 5CO_2 + 6OH^- \quad \text{[Eqn. 4.2]}$$

Denitrification needs anoxic conditions and a carbon source to grow denitrifying bacteria and there are four conditions under which denitrification can occur in the treatment plant:

1. the presence of an abundant and active population of facultative anaerobic denitrifying bacteria
2. the presence of nitrite or nitrate
3. the absence of free molecular oxygen or the presence of an oxygen gradient
4. the presence of soluble CBOD.

In wastewater treatment plants, the presence of denitrifying bacteria is very common. They can enter the system in fecal waste or in groundwater. They are capable of using free molecular oxygen, nitrates, and nitrites to degrade CBOD for gaining energy and carbon. They are floc formers and reproduce very quickly in the system. Denitrifying bacteria represent around 80 % of total floc forming bacteria in a system (Gerardi, 2006).

The high rate of aeration in the BAF indicates that there should be free oxygen present in the system. If this were an activated sludge system, it is unlikely that there would be a zone where free molecules of oxygen are absent. But an oxygen gradient is quite possible in the system. An oxygen gradient happens in flock particle when the flock is >150 μm (Gerardi, 2006). Normally in floc particles, dissolved oxygen and nitrates diffuse to the core. Denitrifying bacteria take the dissolved oxygen to degrade CBOD. But when the

dissolved oxygen is no longer available through the floc, the denitrifying bacteria start to use nitrate instead of dissolved oxygen. So denitrification can happen when particulate matter is present even in the presence of enough DO in the system. There could also be an oxygen gradient between the bulk liquid and the surface of the granular medium, i.e. across the biofilm. Denitrification has been reported in a BAF causing more than 40 % of the total ammonia loss (Han et al., 2001). Moreover Degrémont also reported denitrification in their BIOFOR® (Degrémont, 1991).

The **sixth** possible cause for the imbalance is nitrogen used in cell synthesis. In order to determine if this is a plausible cause, a calculation was performed which took into account the growth of biomass resulting from the consumption of COD in the BAF (Appendix A). The calculations were performed four times, once for each month February to April, using LRWRP laboratory data averaged over the whole month.

The following calculations were performed separately for the inflow and outflow of the BAF. LRWRP SS values were converted to VSS by multiplying a factor of 0.79 (Metcalf and Eddy, 2004) which is the highest ratio of VSS/SS reported for typical composition of untreated domestic wastewater. The nitrogen content of the VSS was then calculated assuming the molecular formula for biomass is $C_5H_7NO_2$. The CBOD reported by LRWRP was converted to COD using 5.65 (Table 4.1). This CBOD is from unfiltered samples (Drca, 2010). The total N is the sum of the nitrogen in the VSS plus the TKN and (NO_2^- + NO_3^-).

Then the decrease in COD between the inflow and the outflow was multiplied by the yield (0.39 g VSS/g COD; Metcalf and Eddy, 2004), and by the nitrogen content of VSS (12.4%) to get the N fixed in the biomass. The difference in total N between inflow and outflow was compared to the N fixed in the biomass. Any difference would be the nitrogen lost as $N_{2(g)}$.

Appendix A shows that the calculated fixed nitrogen were sometimes greater and sometimes less than the difference in total nitrogen, meaning that the observed nitrogen difference could be entirely due to N fixed in the biomass.

4.5 Modeling

4.5.1 Regression

From the analysis of BAF results, it was not clear whether air flow rate was a statistically significant factor for the performance of the BAF. The performance (measured as BOD and ammonia removal after 120 minutes of operation) was correlated to input parameters, such as BOD and NH_3 loading, nominal airflow, water flow rate, pH and temperature. These parameters and their calculated values are listed in Table 4.5.

BOD load removal was calculated by the formula:

$$BOD_{Rem} = (CBOD_{in} - CBOD_{out})\ Q \qquad \text{[Eqn. 4.3]}$$

where,

BOD_{Rem} =BOD load removal (kg/d)

$CBOD_{in}$= Influent CBOD (mg/L)

$CBOD_{out}$=Effluent CBOD (mg/L)

Q= Water flow rate (ML/d)

The ammonia load removal was calculated in a similar manner.

Table 4.5 BAF performance characteristics after 120 minutes of filtration

Date	Air Flow (m3/hr)	Water flow /Cell (ML/d)	BOD_5 Load Eliminated (kg/d)	NH_3 Load Eliminated (kg/d)	$\%BOD_5$ Load Eliminated (kg/d)	$\%NH_3$ Load Eliminated (kg/d)	Air Flow/Water Flow	Temp °C	BOD Load (kg/d)	NH3 Load (Kg/d)	BOD conc. (mg/L)	NH3 Conc. (mg/L)	pH
April-16,2010	1300	20.9	742	231	88.1	78.1	1.50	11.1	842.1	295.7	40.4	14.2	7.05
June-25,2010	1300	19.9	841	127	90.6	82.7	1.57	22.2	927.5	153.3	46.7	7.7	7.34
July-23,2010	1300	19.5	690	91	87.3	79.9	1.60	23.2	789.8	113.9	40.6	5.9	7.82
July-30,2010	1300	21.2	803	104	89.4	80.0	1.47	22.4	898.2	130.3	42.3	6.1	7.70
April-30,2010	1400	20.1	594	170	81.7	74.4	1.67	21.2	726.9	229.3	36.1	11.4	6.93
May-14,2010	1450	19.6	414	161	85.2	78.5	1.78	18.6	486.2	204.8	24.9	10.5	7.38
May-21,2010	1450	19.4	594	163	88.5	76.5	1.79	18.1	671.6	213.2	34.5	11.0	6.71
May-28,2010	1450	20.6	674	215	82.2	78.1	1.69	18.1	820.0	275.1	39.8	13.3	6.79
June-10,2010	1600	19.2	586	216	76.7	86.2	2.00	18.0	764.5	250.8	39.8	13.1	7.23
June-18,2010	1600	21.2	711	136	71.7	82.7	1.81	17.1	991.0	163.8	46.7	7.7	7.34
July-20,2010	1600	20.0	677	228	80.9	78.3	1.92	18.9	837.2	291.3	41.9	14.6	7.30
Feb-14-2010	1700	20.7	668	67	91.0	52.0	1.97	10.2	734.4	128.6	35.5	6.2	7.65
Feb-20,2010	1700	20.1	691	135	86.4	74.4	2.03	12.1	799.5	180.9	39.7	9.0	7.42
Feb-27,2010	1700	20.3	711	217	87.5	71.0	2.01	13.1	812.2	304.8	40.0	15.0	7.85
Mar-12,2010	1700	21.0	735	213	82.6	71.6	1.94	12.9	890.2	297.1	42.4	14.1	7.25
Mar-26,2010	1700	19.5	543	258	68.6	70.0	2.09	20.1	791.5	368.2	40.6	18.9	7.04

Figure 4.11 shows the output for the regression analysis where all parameters were correlated to BOD removal. It can be seen that none of the parameters are statistically significant ($p \leq 0.05$) although together they can predict 92 % of the variability in the BOD load removal.

General Regression Analysis: BOD5 Load Removal

Regression Equation

BOD5 Load Removal(kg/d)-120 = -2947.77 + 1.50078 Air Flow rate(m3/hr) +159.347 Water flow /Cell(ML/d) - 1483.19 Air Flow/Water Flow - 5.60977 Temp 0C - 6.30492 BOD Load (kg/d)-120 min + 140.064 BOD conc.(mg/L) + 54.5364 pH Coefficients

Term	Coef	SE Coef	Temp.	P
Constant	-2947.77	4476.91	-0.65844	0.529
Air Flow R.(m3/hr)	1.50	1.94	0.77216	0.462
Water flow /Cell(ML/d)	159.35	221.75	0.71858	0.493
Air Flow/Water Flow	-1483.19	1636.79	-0.90615	0.391
Temp 0C	-5.61	3.90	-1.43749	0.189
BOD Load (kg/d)-120 min	-6.30	4.05	-1.55618	0.158
BOD conc. (mg/L)	140.06	80.16	1.74721	0.119
pH	54.54	31.56	1.72791	0.122

Summary of Model

S = 40.1475 R-Sq = 91.97% R-Sq(adj) = 84.94%
PRESS = 146485 R-Sq(pred) = 8.73%

Figure 4.11: Minitab output of BOD load removal regressed against BAF performance characteristics

A backward regression was performed to determine the important variables. In this method, the input parameter with the highest p value is removed and the regression is re-run. Then again the highest p value parameter is removed and the regression is run. This is repeated until all remaining variables are significant ($p \leq 0.05$). Figure 4.12 shows the backward regression process. The significant variables remaining after the process were: air flow and water flow ratio, temperature and BOD concentration.

Stepwise Regression: BOD5 Load Removal

Backward elimination Alpha-to-Remove: 0.05

Response is BOD5 Load Removal (kg/d)-120 on 7 predictors, with N = 16

Step	1	2	3	4	5
Constant	-2947.8	263.3	178.2	170.2	611.5
Air Flow R.(m3/hr)	1.5	2.4			
T-Value	0.77	1.59			
P-Value	0.462	0.146			
Water flow /Cell(ML/d)	159				
T-Value	0.72				
P-Value	0.493				
Air Flow/Water Flow	-1483	-2220	-247	-240	-236
T-Value	-0.91	-1.79	-3.49	-4.21	-3.66
P-Value	0.391	0.107	0.006	0.001	0.003
Temp 0C	-5.6	-6.3	-8.6	-8.2	-8.5
T-Value	-1.44	-1.72	-2.38	-3.02	-2.78
P-Value	0.189	0.119	0.038	0.012	0.017
BOD Load (kg/d)-120 min	-6.30	-4.09	-0.10		
T-Value	-1.56	-1.60	-0.18		
P-Value	0.158	0.144	0.861		
BOD conc. (mg/L)	140.1	96.4	17.5	15.4	16.0
T-Value	1.75	1.90	1.42	7.50	6.94
P-Value	0.119	0.090	0.186	0.000	0.000
pH	55	54	65	64	
T-Value	1.73	1.76	2.01	2.09	
P-Value	0.122	0.113	0.073	0.060	
S	40.1	39.1	41.9	40.1	45.3
R-Sq	91.97	91.45	89.04	89.00	84.63
R-Sq(adj)	84.94	85.75	83.56	85.00	80.78
Mallows Cp	8.0	6.5	6.9	4.9	7.3

Figure 4.12: Minitab output of BOD load removal backward regressed against BAF performance characteristics

This left three independent input variables which explain 85 % of the variability in BOD removal. The predictive model for BOD removal becomes:

BOD removal = 611.5-236 air/water flow -8.5 temp +16.0 BOD concentration.

[Eqn. 4.4]

Reactions are not normally a linear function of temperature, so a better model can be created using a non linear function for temperature. The negative coefficient in front of air/ water flow shows that BOD removal is reduced with higher airflow rate which means a higher BOD removal is possible with lower airflow rate

A similar approach was used to find a predictive model for the NH_3 removal. Figure 4.13 shows that when the all input variables are regressed against NH_3 removal, there were no significant variables, but 97 % of the variation could be explained.

General Regression Analysis: NH3 Load Removal

Regression Equation

NH3 Load Removal(kg/d)-120 m = -2652.01 - 2.50468 Air Flow Rate (m3/hr) +131.746 Water flow /Cell(ML/d) + 2151.13Air Flow/Water Flow + 2.04932 Temp 0C +6.14121 NH3 Load(Kg/d)120 min - 111.176 NH3 Conc. (mg/L) - 13.1511 pH

Coefficients

Term	Coef	SE Coef	T	P
Constant	-2652.01	1480.34	-1.79149	0.111
Air Flow R.(m3/hr)	-2.50	1.26	-1.98765	0.082
Water flow /Cell(ML/d)	131.75	71.52	1.84222	0.103
Air Flow/Water Flow	2151.13	1094.72	1.96501	0.085
Temp 0C	2.05	1.46	1.40616	0.197
NH3 Load(Kg/d)120 min	6.14	3.04	2.02115	0.078
NH3 Conc. (mg/L)	-111.18	62.38	-1.78220	0.113
pH	-13.15	12.27	-1.07142	0.315

Summary of Model

S = 12.9066 R-Sq = 97.26% R-Sq(adj) = 94.86%
PRESS = 9040.31 R-Sq(pred) = 81.39%

Figure 4.13: Minitab output of NH_3 load removal regressed against BAF performance characteristics

So a backward regression was performed and as a result (Figure 4.14), the only significant variable was NH_3 loading. The following model explains 97 % variability in the NH_3 removal.

NH_3 load removal = 7.120 + 0.727 NH_3 load removal [Eqn. 4.5]

Stepwise Regression: NH3 Load Removal

Backward elimination. Alpha-to-Remove: 0.05

Response is NH3 Load Removal(kg/d)-120 m on 7 predictors, with N =16

Step	1	2	3	4	5	6	7
Constant	-2652.01	-2326.75	-1585.22	-741.57	65.19	66.82	7.120
Air Flow R.(m3/hr)	-2.505	-2.140	-1.477	-0.625	-0.097	-0.045	
T-Value	-1.99	-1.75	-1.33	-0.93	-1.40	-2.05	
P-Value	0.082	0.114	0.214	0.373	0.187	0.061	
Water flow /Cell(ML/d)	132	112	80	40			
T-Value	1.84	1.61	1.22	0.79			
P-Value	0.103	0.142	0.250	0.447			
Air Flow/Water Flow	2151	1824	1230	494	45		
T-Value	1.97	1.72	1.29	0.86	0.79		
P-Value	0.085	0.119	0.227	0.406	0.444		
Temp 0C	2.0	1.7					
T-Value	1.41	1.19					
P-Value	0.197	0.264					
NH3 Load(Kg/d)120 min	6.141	5.192	2.961	0.743	0.758	0.765	0.727
T-Value	2.02	1.77	1.29	13.84	15.50	16.10	15.12
P-Value	0.078	0.110	0.227	0.000	0.000	0.000	0.000
NH3 Conc. (mg/L)	-111	-91	-46				
T-Value	-1.78	-1.52	-0.96				
P-Value	0.113	0.163	0.358				
pH	-13						
T-Value	-1.07						
P-Value	0.315						
S	12.9	13.0	13.3	13.2	13.0	12.8	14.2
R-Sq	97.26	96.86	96.37	96.03	95.81	95.59	94.16
R-Sq(adj)	94.86	94.77	94.55	94.59	94.76	94.91	93.74
Mallows Cp	8.0	7.1	6.6	5.6	4.2	2.9	5.0

Figure 4.14: Minitab output of NH_3 load removal backward Regressed against BAF performance characteristics

It is noticed that air flow rate and air/water flow ratio are not significant variables effecting NH_3 removal. This could mean that the BAF had sufficient oxygen for NH_3 and reducing airflow rate to 1300 m^3/h did not adversely effect NH_3 consumption. Theoretically, NH_3 elimination requires oxygen in the conversion to NO_2^-. Therefore at some lower aeration rate NH_3 elimination should be effected. It would be useful to test the BAF at aeration rates below 1300 m^3/h.

Figure 4.15 shows the effect of BOD loading on BOD elimination. From this graph, it can be seen that the lowest airflow rate achieved the highest BOD removal, even though the BOD loading for these points is quite high. If % BOD removal is considered, it is observed that lower airflow was 89-91 % efficient in removing BOD load (Figure 4.16). With the airflow rate of 1300 m^3/h it is showing the highest average removal efficiency.

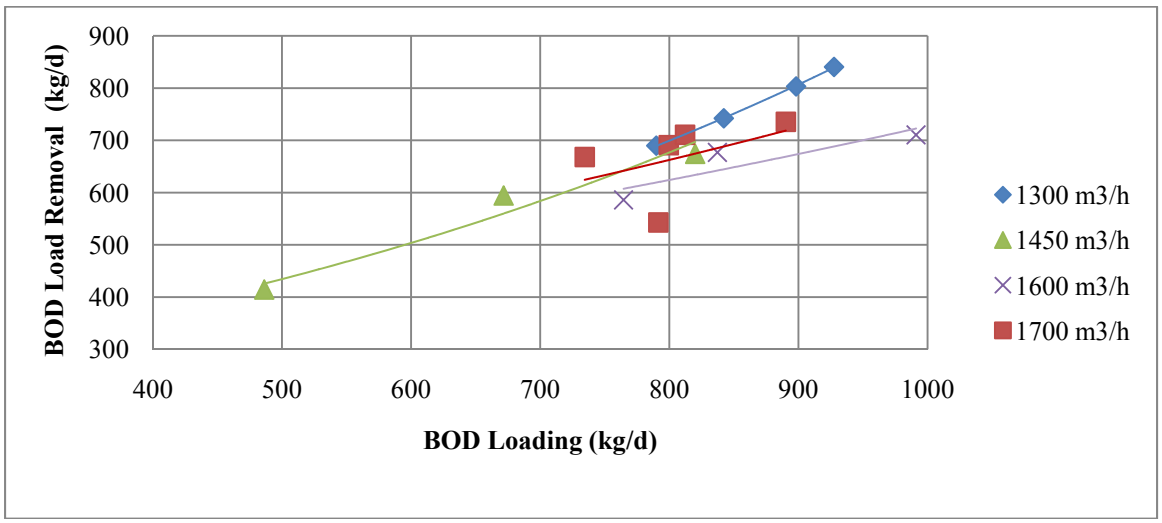


Figure 4.15: BOD load removal vs. BOD loading at different air flow rates120 minutes after start of filtration

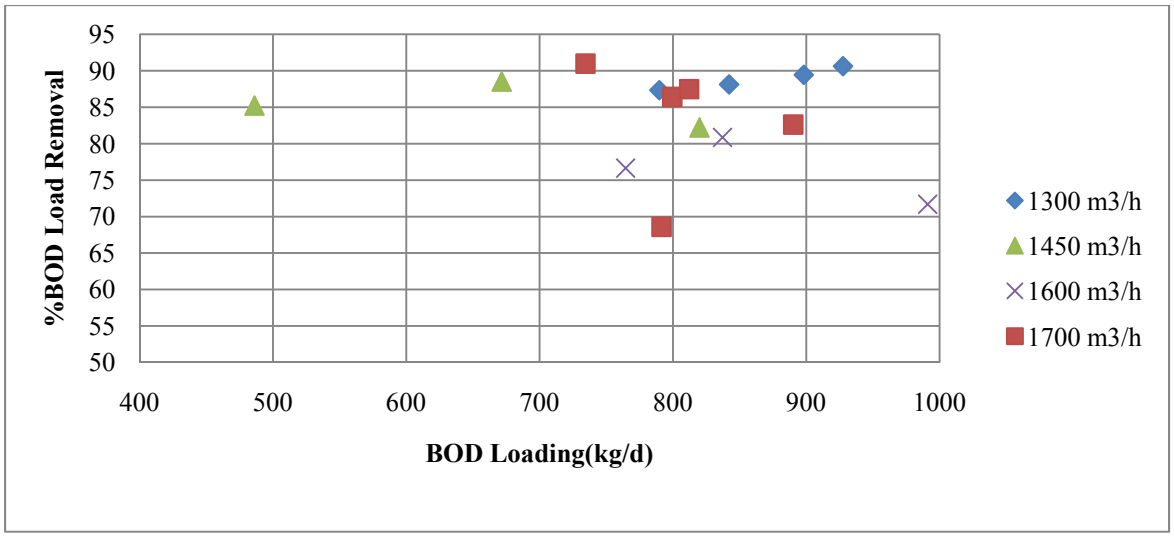


Figure 4.16: % BOD load removal vs. BOD loading at different air flow rates 120 minutes after start of filtration

For different air/water flow ratios in the cell, Figure 4.17 shows a better BOD load removal at 1300 m^3/h, This is again an indication that lower air flow rate was more efficient in BOD removal.

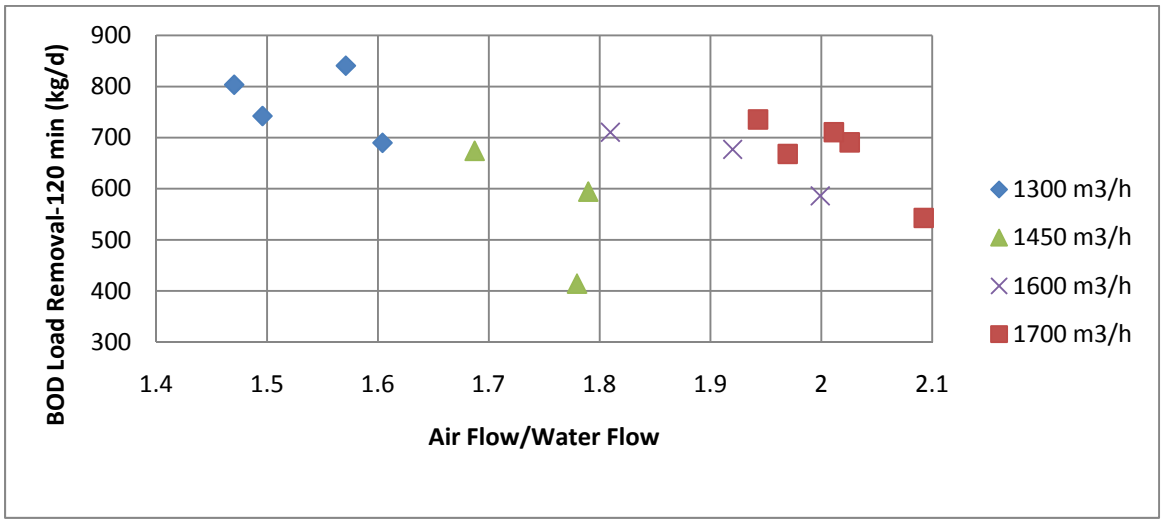


Figure 4.17 BOD load Removal vs. Air/Water Flow at different air flow rates 120 minutes after start of filtration

For NH_4^+ load removal, 1700 m^3/h nominal airflow seems to result in the most NH_4^+ removal (Figure 4.18) but the highest load removal corresponds to the highest loading. At

moderate loads, the NH_4^+ load removal is no different than at 1300 m^3/h. In fact the % NH_4^+ removal is essentially the same as 1300 m^3/h air flow rate and all these are superior to the case at 1700 m^3/h. For optimum removal efficiency of both NH_3 and BOD, 1300 m^3/h should be the nominal airflow for the system. The BAF control system can currently be set to a minimum of 1300 m^3/h, which is a limitation of the current study. In fact, a lower value of airflow should be explored.

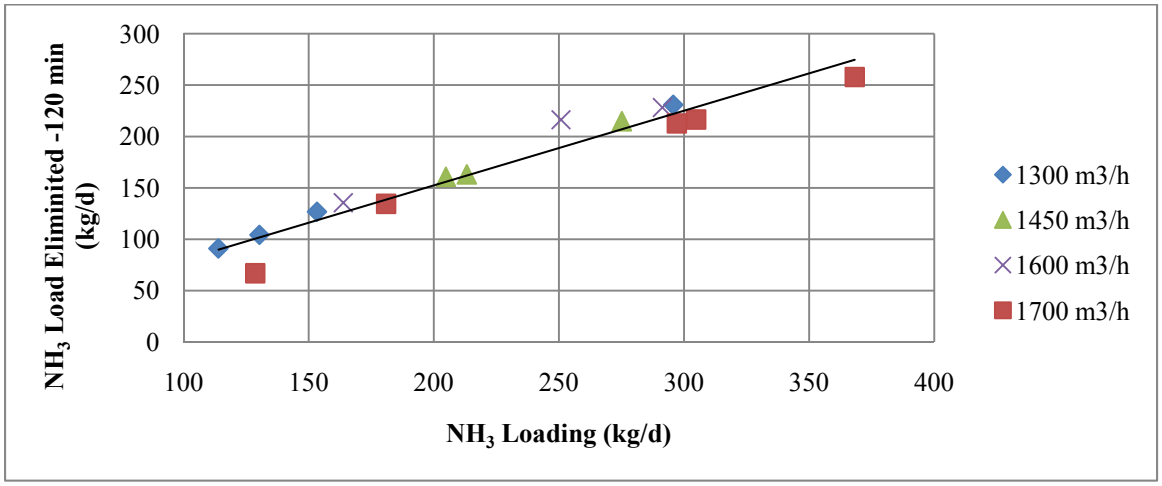


Figure 4.18: NH_3 load removal vs. NH_3 at different air flow rates 120 minutes after start of filtration

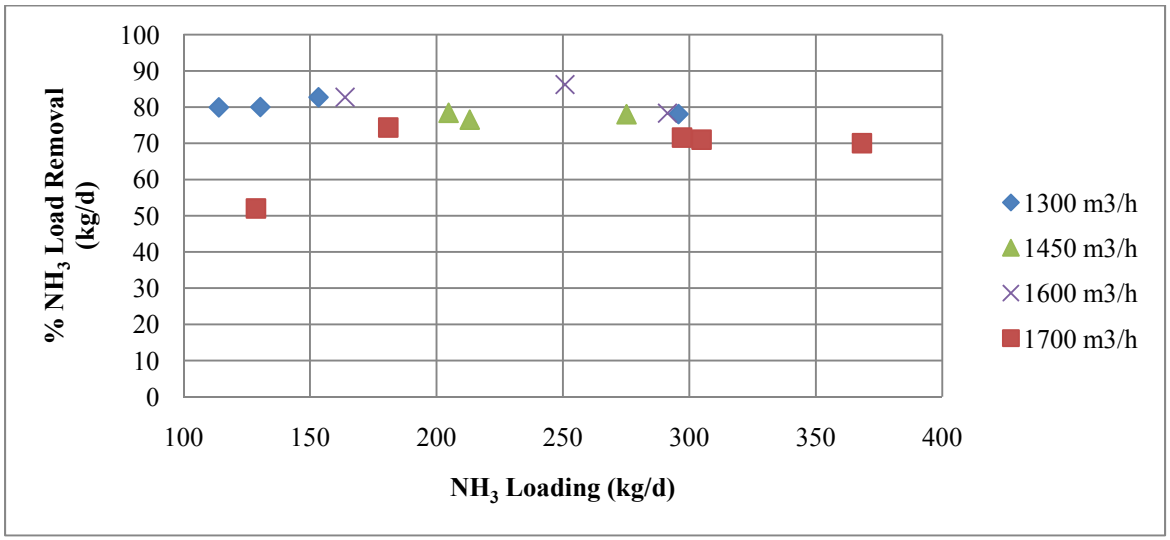


Figure 4.19: % NH_3 load removal vs. Air/Water Flow at different air flow rates after 120 min during filtration

4.5.2 Calculation of re-aeration coefficient

In the BAF, the average re aeration coefficient was calculated based on a mass balance of oxygen across the second (25 %-50 %) and third (50 %-75 %) layers of the BAF. First the saturation concentration of oxygen must have to be calculated, and this required an correction due to the hydrostatic pressure of depth. Cell number 7 was divided according to sample collection heights of 0 %, 25 %, 50 %, 75 % and 100 %. Static pressure can be calculated easily at different heights of the cell. Let, P1, P2, P3, P4 be the static pressures at 100 %, 75 %, 50 %, and 25 % of the cell heights respectively.

At the top, i.e., at 100 %, the barometric pressure was 760 mm Hg

At 75% P2 = SP + ρgh

$$= 760 \text{ mm Hg} + 1000 \text{ kg/m}^3 \text{ x } 9.81 \text{ N/kg x } 1.485 \text{ m x } \frac{760 \text{ mm}\frac{\text{Hg}}{\text{atm}}.}{101300\frac{\text{Pa}}{\text{atm}}.}$$

$$= 760 \text{ mm Hg} + 1.485 \text{ m x } 73.6 \text{ mm Hg/m}$$

$$= 869 \text{ mm Hg}$$

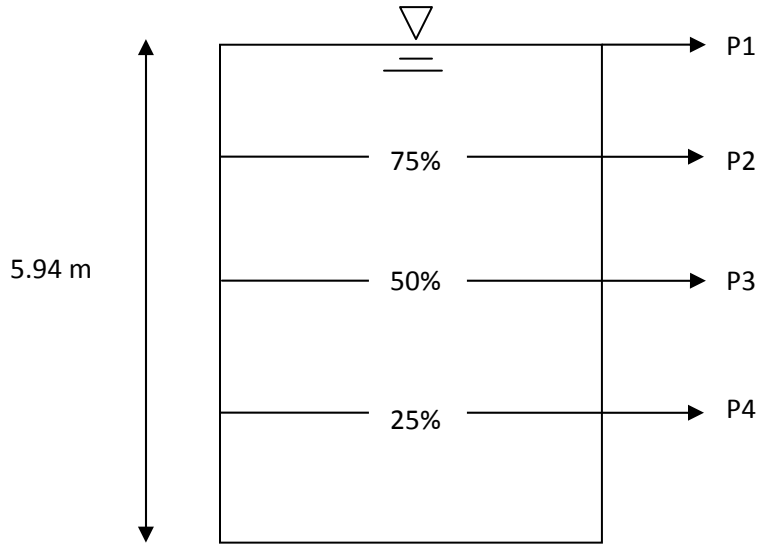


Figure 4.20: Pressure at different heights of the cell

Similarly, P3 =978 mm Hg

and P4 =1087 mm Hg

Colt (1984) gives the saturation oxygen concentration as

$DO^*=DO_{760}\ (P-P_{H2O})\ /(760-P_{H2O})$ [Eqn.4.7]

where,

DO^* = oxygen saturation concentration at required barometric pressure (from Table 1 in Colt, 1984), mg/L

DO_{760}= saturation concentration at 760 mm, mg/L

P =Pressure in at depth, mm of Hg

P_{H2O} =Vapor pressure of water, mm Hg (from Table 5 in Colt, 1984)

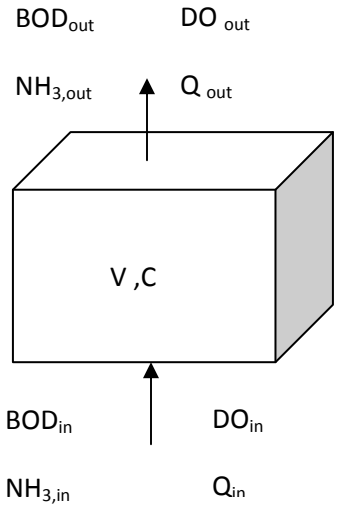


Figure 4.21: Mass balance of oxygen in a layer of the BAF

Mass balance:

Accumulation =Inflow-Outflow-Oxygen Consumed +Reaeration

$V\ dDO/dt = DO_{in}\ Q_{in} - DO_{out}\ Q_{out} - (\Delta BOD + 4.3\Delta NH_3)Q + K_a V(DO^* - DO)$ [Eqn. 4.8]

where,

V = volume of each layer of cell, L

DO_{in} = DO concentration flowing into the layer, mg/L

C_{out} = DO concentration flowing out of the layer, mg/L

DO_{in} = Wastewater inflow rate, L/h

Q_{out} = Wastewater outflow rate, L/h

$\Delta BOD = BOD_{in} - BOD_{out}$ = change in BOD within the layer, mg/L

$\Delta NH_3 = NH_{3in} - NH_{3\,out}$ = change in NH_3 within the layer, mg-N/L

K_a = volumetric re-aeration coefficient, h^{-1}

DO_{sat} = Saturated DO (average value between top and bottom of the cell (adjusted for temperature in the cell), mg/L

DO = DO concentration in the cell = $(DO_{in}+DO_{out})/2$, mg/L

Here, for each gram of ammonia nitrogen converted, 4.3 grams of O_2 were utilized when cell synthesis was considered in the system (Metcalf and eddy, Inc., 2004).

Assuming steady state,

$dC/dt = 0$

i.e., $0 = DO_{in}Q_{in} - DO_{out}Q_{out} - (\Delta BOD + 4.3\Delta COD)Q + K_aV(DO_{sat}-DO)$ [Eqn.4.9]

if $X1 = DO_{in}\,Q_{in} - DO_{out}\,Q_{out} - (\Delta BOD + 4.3\Delta COD)Q$

and $X2 = V(C_{sat}-C)$, then

$0 = X1 + K_aX2 = X1 + K_{a,20}\,\theta^{(T-20)}\,X2$ [Eqn. 4.10]

where, $K_{a,20}$ = volumetric re-aeration coefficient at $20^0C, h^{-1}$

T=Temperature, °C

θ =temperature correction factor

From Equation 4.9 rearrange and take the log

$\log(-X1/X2) = \log K_{a,20} + (T-20)\log\theta$ [Eqn. 4.11]

Measured data (Table 4.1 Table 4.2) were used to calculate X1/X2 in the 25 %-50 % layer and the 50 %-75 % layer through the cell for all the tests date at 30 minutes, 60minutes and 120minutes (Table 4.6). Then log (-X1/X2) values were plotted against T-20 values (Figure 4.22). In this Figure, a linear equation of y= 0.0451 x+ 1.9134 was fitted by Excel which gave:

$\log K_{a,20} = 1.9134$

$K_{a,20} = 81.92$ /hr =1966/d

and $\log\theta = 0.0451$

$\theta = 1.09$

For lakes and rivers, the K_a is 0.05/d to 12.2/d and θ is 1.005 to 1.030 when an average depth of 1 to 30 feet and velocity of 0.5-1.6 ft/s are used (Thomann and Muller, 1987). The current study is in a BAF where aeration is promoted by fine-bubble diffusers. This

would result in a higher re-aeration coefficient than when the oxygen transfer occurs only at the free surface of a lake or river.

O' Connor's formulation (Thomann and Muller, 1987) for the re-aeration coefficient was used to compare K_a and K_L (K_{La}) values reported in the literature:

$$K_a = K_L / H \qquad \text{[Eqn 4.12]}$$

where K_L = oxygen transfer coefficient, m/d

H =is average depth for a particular stretch of river, the depth, H, is taken as the ratio of volume to surface area.

In BAF, the surface area for oxygen transfer is the total surface area of the bubbles. Finding this value is difficult and requires further study. But with a known value of H, the oxygen transfer coefficient for the BAF can be calculated.

Table 4.6: Determination of Ka value

Test Number	Region	C (mg/L)	Csat at 760 mm Hg(mg/L)	PH_20	Csat individual pressure (mg/L)	Δ BOD (mg/L)	Δ NH_3 (mg/L)	V (L)	t (°C)	$C_{in}Q_{in}$ (mg/h)	$C_{out}Q_{out}$ (mg/h)	(Δ BOD+4.3Δ NH_3)*Q	X1	X2	-X1/X2	log (-X1/X2)	T-20
1	30 mn-25%-50%	8.33	11.12	9.59	12.74	8.98	0.53	35000	10.60	179	171	9.85.E+06	-9.85.E+06	1.55.E+05	63.76	1.80	-9.40
	30 mn-50%-75%	8.42	11.20	9.40	12.83	1.51	0.72	35000	10.30	7123	7604	4.03.E+06	-4.03.E+06	1.54.E+05	26.09	1.42	-9.70
	60 mn-25%-50%	7.72	10.87	10.24	12.45	4.04	0.85	35000	11.60	6603	6165	6.37.E+06	-6.37.E+06	1.66.E+05	38.42	1.58	-8.40
	60 mn-50%-75%	7.57	11.00	9.91	12.59	5.71	0.24	35000	11.10	6165	6355	5.58.E+06	-5.58.E+06	1.76.E+05	31.71	1.50	-8.90
	120 mn-25%-50%	9.04	10.92	10.11	12.51	1.01	0.66	35000	11.40	7294	7335	3.12.E+06	-3.12.E+06	1.22.E+05	25.63	1.41	-8.60
	120 mn-50%-75%	8.82	10.82	10.38	12.39	2.03	0.97	35000	11.80	7335	6938	5.02.E+06	-5.02.E+06	1.25.E+05	40.08	1.60	-8.20
2	30 mn-25%-50%	7.75	10.67	10.80	12.23	4.82	0.87	35000	12.40	6057	6639	7.02.E+06	-7.02.E+06	1.57.E+05	44.75	1.65	-7.60
	30 mn-50%-75%	8.00	10.75	10.59	12.31	-0.11	0.17	35000	12.10	6639	6475	5.23.E+05	-5.23.E+05	1.51.E+05	3.47	0.54	-7.90
	60 mn-25%-50%	7.58	10.65	10.87	12.20	2.92	0.88	35000	12.50	6154	7023	5.82.E+06	-5.82.E+06	1.62.E+05	36.00	1.56	-7.50
	60 mn-50%-75%	7.90	10.60	11.01	12.14	2.44	0.23	35000	12.70	7023	6701	2.98.E+06	-2.98.E+06	1.49.E+05	20.01	1.30	-7.30
	120 mn-25%-50%	7.35	10.72	10.66	12.28	2.58	0.60	35000	12.20	5481	6420	4.18.E+06	-4.19.E+06	1.73.E+05	24.25	1.38	-7.80
	120 mn-50%-75%	8.04	10.67	10.80	12.23	-2.51	2.23	35000	12.40	6420	6590	5.73.E+06	-5.73.E+06	1.47.E+05	39.04	1.59	-7.60
3	30 mn-25%-50%	8.17	10.43	11.53	11.95	3.76	1.13	35000	13.40	6834	7455	7.55.E+06	-7.55.E+06	1.33.E+05	56.91	1.76	-6.60
	30 mn-50%-75%	8.42	10.51	11.31	12.04	2.08	0.23	35000	13.10	7455	7280	2.67.E+06	-2.67.E+06	1.27.E+05	21.10	1.32	-6.90
	60 mn-25%-50%	8.10	10.41	11.61	11.93	5.44	1.30	35000	13.50	6272	7133	9.12.E+06	-9.12.E+06	1.34.E+05	68.08	1.83	-6.50
	60 mn-50%-75%	8.44	10.36	11.76	11.87	1.27	0.34	35000	13.70	7133	6827	2.25.E+06	-2.25.E+06	1.20.E+05	18.73	1.27	-6.30
	120 mn-25%-50%	7.94	10.48	11.38	12.01	6.46	1.01	35000	13.20	6964	8062	1.02.E+07	-1.02.E+07	1.42.E+05	71.74	1.86	-6.80
	120 mn-50%-75%	8.63	10.43	11.53	11.95	-0.99	3.73	35000	13.40	8062	8261	1.42.E+07	-1.42.E+07	1.16.E+05	122.20	2.09	-6.60
4	30 mn-25%-50%	8.06	10.51	11.31	12.04	3.76	1.07	35000	13.10	6738	7359	7.30.E+06	-7.30.E+06	1.39.E+05	52.38	1.72	-6.90
	30 mn-50%-75%	8.31	10.51	11.31	12.04	2.09	0.21	35000	13.10	7359	7184	2.63.E+06	-2.63.E+06	1.30.E+05	20.17	1.30	-6.90
	60 mn-25%-50%	7.99	10.51	11.31	12.04	5.44	1.22	35000	13.10	6048	6890	8.65.E+06	-8.65.E+06	1.42.E+05	61.10	1.79	-6.90
	60 mn-50%-75%	8.33	10.51	11.31	12.04	1.27	0.32	35000	13.10	6890	6590	2.14.E+06	-2.14.E+06	1.30.E+05	16.47	1.22	-6.90
	120 mn-25%-50%	7.83	10.51	11.23	12.04	6.46	0.95	35000	13.00	6733	7811	9.79.E+06	-9.79.E+06	1.47.E+05	66.49	1.82	-7.00
	120 mn-50%-75%	8.52	10.53	11.23	12.06	-1.28	3.51	35000	13.00	7811	8006	1.28.E+07	-1.28.E+07	1.24.E+05	103.35	2.01	-7.00
5	30 mn-25%-50%	7.95	10.77	10.52	12.34	2.99	1.42	35000	12.00	6603	7221	7.91.E+06	-7.91.E+06	1.54.E+05	51.47	1.71	-8.00
	30 mn-50%-75%	8.20	10.77	10.52	12.34	1.66	0.28	35000	12.00	7221	7047	2.51.E+06	-2.51.E+06	1.45.E+05	17.31	1.24	-8.00
	60 mn-25%-50%	7.88	10.77	10.52	12.34	4.33	1.63	35000	12.00	6363	7263	9.80.E+06	-9.80.E+06	1.56.E+05	62.86	1.80	-8.00
	60 mn-50%-75%	8.22	10.77	10.52	12.34	1.01	0.43	35000	12.00	7263	6943	2.46.E+06	-2.46.E+06	1.44.E+05	17.06	1.23	-8.00
	120 mn-25%-50%	7.72	10.75	10.59	12.31	5.23	1.25	35000	12.10	5819	6765	8.64.E+06	-8.64.E+06	1.61.E+05	53.82	1.73	-7.90
	120 mn-50%-75%	8.41	10.72	10.66	12.28	-1.11	4.67	35000	12.20	6765	6936	1.54.E+07	-1.54.E+07	1.36.E+05	113.85	2.06	-7.80

Table 4.6 (continued): Determination of Ka value

Test Number	Region	C (mg/L)	Csat at 760 mm Hg(mg/L)	PH_20	Csat individual pressure (mg/L)	Δ BOD (mg/L)	Δ NH_3 (mg/L)	V (L)	t (°C)	$C_{in}Q_{in}$ (mg/h)	$C_{out}Q_{out}$ (mg/h)	(Δ BOD+4.3Δ NH_3)*Q	X1	X2	-X1/X2	log (-X1/X2)	T-20
6	30 mn-25%-50%	4.88	9.19	16.90	10.54	9.20	3.74	35000	19.40	4237	4254	2.20.E+07	-2.20.E+07	1.98.E+05	111.02	2.05	-0.60
	30 mn-50%-75%	4.95	9.45	15.48	10.83	10.71	0.40	35000	18.00	4254	4350	1.08.E+07	-1.08.E+07	2.06.E+05	52.54	1.72	-2.00
	60 mn-25%-50%	5.09	9.39	15.78	10.77	9.03	4.60	35000	18.30	4556	4195	2.48.E+07	-2.48.E+07	1.99.E+05	124.56	2.10	-1.70
	60 mn-50%-75%	5.35	9.39	15.78	10.77	6.95	1.50	35000	18.30	4195	5003	1.15.E+07	-1.15.E+07	1.90.E+05	60.82	1.78	-1.70
	120 mn-25%-50%	4.55	9.41	15.68	10.79	11.16	1.96	35000	18.20	3387	4104	1.62.E+07	-1.62.E+07	2.19.E+05	73.92	1.87	-1.80
	120 mn-50%-75%	5.10	9.43	15.58	10.81	10.46	1.06	35000	18.10	4104	4294	1.24.E+07	-1.24.E+07	2.00.E+05	61.86	1.79	-1.90
7	30 mn-25%-50%	4.82	9.15	17.11	10.49	6.07	4.24	35000	19.60	4032	4049	2.04.E+07	-2.04.E+07	1.99.E+05	102.51	2.01	-0.40
	30 mn-50%-75%	4.89	9.41	15.68	10.79	7.08	1.56	35000	18.20	4049	4141	1.16.E+07	-1.16.E+07	2.07.E+05	55.93	1.75	-1.80
	60 mn-25%-50%	4.71	9.28	16.38	10.64	6.97	5.09	35000	18.90	4157	3803	2.44.E+07	-2.44.E+07	2.08.E+05	117.45	2.07	-1.10
	60 mn-50%-75%	4.97	9.36	15.97	10.73	6.30	2.79	35000	18.50	3803	4597	1.55.E+07	-1.55.E+07	2.01.E+05	76.77	1.89	-1.50
	120 mn-25%-50%	4.78	9.37	15.88	10.75	9.26	2.21	35000	18.40	3776	4533	1.63.E+07	-1.63.E+07	2.09.E+05	78.02	1.89	-1.60
	120 mn-50%-75%	5.33	9.39	15.78	10.77	8.67	2.53	35000	18.30	4533	4733	1.70.E+07	-1.70.E+07	1.91.E+05	89.23	1.95	-1.70
8	30 mn-25%-50%	6.55	9.39	15.78	10.77	6.80	2.98	35000	18.30	5167	5509	1.60.E+07	-1.60.E+07	1.48.E+05	108.20	2.03	-1.70
	30 mn-50%-75%	6.45	9.37	15.88	10.75	1.34	0.32	35000	18.40	5509	4996	2.22.E+06	-2.22.E+06	1.51.E+05	14.73	1.17	-1.60
	60 mn-25%-50%	5.12	9.41	15.68	10.79	7.80	3.53	35000	18.20	4154	4277	1.90.E+07	-1.90.E+07	1.99.E+05	95.42	1.98	-1.80
	60 mn-50%-75%	5.26	9.41	15.68	10.79	7.05	1.15	35000	18.20	4277	4385	9.87.E+06	-9.87.E+06	1.94.E+05	50.96	1.71	-1.80
	120 mn-25%-50%	5.51	9.39	15.78	10.77	10.36	1.45	35000	18.30	4505	4775	1.40.E+07	-1.40.E+07	1.84.E+05	75.97	1.88	-1.70
	120 mn-50%-75%	5.72	9.43	15.58	10.81	1.80	0.78	35000	18.10	4775	4850	4.34.E+06	-4.34.E+06	1.78.E+05	24.36	1.39	-1.90
9	30 mn-25%-50%	5.02	9.19	17.98	10.54	5.82	4.17	35000	20.40	4058	4074	1.92.E+07	-1.92.E+07	1.93.E+05	99.66	2.00	0.40
	30 mn-50%-75%	5.09	9.45	16.48	10.84	7.92	1.48	35000	19.00	4074	4163	1.16.E+07	-1.16.E+07	2.01.E+05	57.44	1.76	-1.00
	60 mn-25%-50%	5.24	9.32	17.22	10.68	6.68	5.08	35000	19.70	4514	4167	2.36.E+07	-2.36.E+07	1.91.E+05	124.02	2.09	-0.30
	60 mn-50%-75%	5.50	9.39	16.79	10.77	9.43	2.66	35000	19.30	4167	4945	1.73.E+07	-1.73.E+07	1.84.E+05	93.74	1.97	-0.70
	120 mn-25%-50%	5.51	9.41	16.69	10.79	8.88	2.18	35000	19.20	4179	4896	1.51.E+07	-1.51.E+07	1.85.E+05	81.39	1.91	-0.80
	120 mn-50%-75%	6.06	9.43	16.59	10.81	11.71	2.43	35000	19.10	4896	5085	1.83.E+07	-1.83.E+07	1.67.E+05	109.69	2.04	-0.90
10	30 mn-25%-50%	4.80	8.65	20.45	9.92	6.80	6.14	35000	22.50	4160	4092	2.85.E+07	-2.85.E+07	1.79.E+05	159.20	2.20	2.50
	30 mn-50%-75%	4.87	8.58	20.95	9.84	9.24	2.11	35000	22.90	4092	4272	1.57.E+07	-1.57.E+07	1.74.E+05	90.34	1.96	2.90
	60 mn-25%-50%	6.63	8.76	18.43	10.05	7.80	6.97	35000	21.80	5951	5585	3.29.E+07	-3.29.E+07	1.20.E+05	274.28	2.44	1.80
	60 mn-50%-75%	6.89	8.75	18.54	10.03	11.00	3.53	35000	21.90	5585	6403	2.28.E+07	-2.28.E+07	1.10.E+05	206.92	2.32	1.90
	120 mn-25%-50%	6.90	8.75	18.54	10.03	6.95	2.71	35000	21.90	5534	6279	1.59.E+07	-1.59.E+07	1.10.E+05	145.14	2.16	1.90

Table 4.6 (Continued): Determination of Ka value

Test Number	Region	C (mg/L)	Csat at 760 mm Hg(mg/L)	PH_20	Csat individual pressure (mg/L)	Δ BOD (mg/L)	Δ NH_3 (mg/L)	V (L)	t (°C)	$C_{in}Q_{in}$ (mg/h)	$C_{out}Q_{out}$ (mg/h)	(Δ BOD+4.3Δ NH_3)*Q	X1	X2	-X1/X2	log (-X1/X2)	T-20
11	30 mn-25%-50%	5.49	8.85	19.00	10.15	6.34	6.54	35000	21.30	4354	4426	2.76.E+07	-2.76.E+07	1.63.E+05	168.99	2.23	1.30
	30 mn-50%-75%	5.58	8.78	19.47	10.07	8.63	2.76	35000	21.70	4426	4506	1.64.E+07	-1.64.E+07	1.57.E+05	104.24	2.02	1.70
	60 mn-25%-50%	5.82	9.15	18.20	10.50	3.59	5.80	35000	20.60	4609	4762	2.30.E+07	-2.30.E+07	1.64.E+05	140.31	2.15	0.60
	60 mn-50%-75%	6.06	9.13	18.31	10.48	4.12	4.55	35000	20.70	4762	5004	1.91.E+07	-1.91.E+07	1.55.E+05	123.50	2.09	0.70
	120 mn-25%-50%	6.33	9.13	18.31	10.48	6.49	4.39	35000	20.70	5049	5211	2.06.E+07	-2.06.E+07	1.45.E+05	141.69	2.15	0.70
	120 mn-50%-75%	6.67	8.90	18.66	10.21	9.67	3.58	35000	21.00	5211	5600	2.03.E+07	-2.03.E+07	1.24.E+05	164.08	2.22	1.00
12	30 mn-25%-50%	5.59	9.19	17.76	10.54	6.96	0.00	35000	20.20	4942	4942	6.15.E+06	-6.15.E+06	1.73.E+05	35.54	1.55	0.20
	30 mn-50%-75%	5.68	9.19	18.20	10.54	9.47	0.00	35000	20.60	5022	5022	8.37.E+06	-8.37.E+06	1.70.E+05	49.24	1.69	0.60
	60 mn-25%-50%	5.90	9.36	17.00	10.73	3.94	0.00	35000	19.50	5276	5276	3.52.E+06	-3.52.E+06	1.69.E+05	20.85	1.32	-0.50
	60 mn-50%-75%	6.09	9.34	17.11	10.71	4.52	0.00	35000	19.60	5445	5445	4.04.E+06	-4.04.E+06	1.62.E+05	25.01	1.40	-0.40
	120 mn-25%-50%	6.46	9.34	17.11	10.71	7.12	0.00	35000	19.60	5712	5712	6.30.E+06	-6.30.E+06	1.49.E+05	42.38	1.63	-0.40
	120 mn-50%-75%	6.66	9.28	17.43	10.64	10.62	0.00	35000	19.90	5889	5889	9.39.E+06	-9.39.E+06	1.39.E+05	67.37	1.83	-0.10
13	30 mn-25%-50%	5.64	9.22	17.76	10.58	6.96	4.19	35000	20.20	4626	4700	2.07.E+07	-2.07.E+07	1.73.E+05	119.52	2.08	0.20
	30 mn-50%-75%	5.73	9.15	18.20	10.50	9.47	1.76	35000	20.60	4700	4783	1.41.E+07	-1.41.E+07	1.67.E+05	84.60	1.93	0.60
	60 mn-25%-50%	6.00	9.36	17.00	10.73	3.94	3.43	35000	19.50	4809	4963	1.52.E+07	-1.52.E+07	1.66.E+05	92.04	1.96	-0.50
	60 mn-50%-75%	6.24	9.34	17.11	10.71	4.52	2.69	35000	19.60	4963	5208	1.31.E+07	-1.31.E+07	1.56.E+05	83.92	1.92	-0.40
	120 mn-25%-50%	6.56	9.34	17.11	10.71	7.12	2.60	35000	19.60	5200	5361	1.47.E+07	-1.47.E+07	1.45.E+05	101.52	2.01	-0.40
	120 mn-50%-75%	6.90	9.28	17.43	10.64	10.62	2.12	35000	19.90	5361	5748	1.59.E+07	-1.59.E+07	1.31.E+05	121.26	2.08	-0.10
14	30 mn-25%-50%	4.78	8.30	23.21	9.53	6.96	3.66	35000	24.60	3892	4075	1.89.E+07	-1.89.E+07	1.66.E+05	113.68	2.06	4.60
	30 mn-50%-75%	5.02	8.32	23.07	9.55	8.12	0.39	35000	24.50	4075	4283	8.18.E+06	-8.18.E+06	1.59.E+05	51.54	1.71	4.50
	60 mn-25%-50%	4.64	8.32	23.07	9.55	7.99	4.73	35000	24.50	3697	4109	2.39.E+07	-2.39.E+07	1.72.E+05	138.65	2.14	4.50
	60 mn-50%-75%	5.08	8.30	23.21	9.53	7.22	1.54	35000	24.60	4109	4438	1.17.E+07	-1.17.E+07	1.56.E+05	74.69	1.87	4.60
	120 mn-25%-50%	4.87	8.26	23.63	9.48	10.62	2.02	35000	24.90	4008	4194	1.62.E+07	-1.62.E+07	1.61.E+05	100.74	2.00	4.90
	120 mn-50%-75%	5.10	8.27	23.48	9.50	9.94	1.09	35000	24.80	4194	4387	1.23.E+07	-1.23.E+07	1.54.E+05	79.89	1.90	4.80
15	30 mn-25%-50%	5.96	8.70	20.08	9.98	6.64	3.59	35000	22.20	4790	4863	1.79.E+07	-1.79.E+07	1.41.E+05	127.14	2.10	2.20
	30 mn-50%-75%	6.05	8.63	20.57	9.90	9.03	1.51	35000	22.60	4863	4944	1.26.E+07	-1.26.E+07	1.35.E+05	93.30	1.97	2.60
	60 mn-25%-50%	6.32	8.65	20.45	9.92	3.76	2.61	35000	22.50	5095	5251	1.23.E+07	-1.23.E+07	1.26.E+05	97.30	1.99	2.50
	60 mn-50%-75%	6.56	8.63	20.57	9.90	4.31	2.04	35000	22.60	5251	5497	1.07.E+07	-1.07.E+07	1.17.E+05	91.73	1.96	2.60
	120 mn-25%-50%	6.67	8.63	20.57	9.90	6.79	1.97	35000	22.60	5259	5419	1.22.E+07	-1.22.E+07	1.13.E+05	108.21	2.03	2.60
	120 mn-50%-75%	7.01	8.58	20.95	9.84	10.12	1.61	35000	22.90	5419	5803	1.36.E+07	-1.36.E+07	9.91.E+04	137.51	2.14	2.90

Table 4.6 (continued): Determination of Ka value

Test Number	Region	C (mg/L)	Csat at 760 mm Hg(mg/L)	PH_20	Csat individual pressure (mg/L)	Δ BOD (mg/L)	Δ NH_3 (mg/L)	V (L)	t (^oC)	$C_{in}Q_{in}$ (mg/h)	$C_{out}Q_{out}$ (mg/h)	(Δ BOD+4.3Δ NH_3)*Q	X1	X2	-X1/X2	log (-X1/X2)	T-20
16	30 mn-25%-50%	5.82	8.51	21.46	9.77	7.13	3.77	35000	23.30	5102	5181	2.07.E+07	-2.07.E+07	1.38.E+05	149.31	2.17	3.30
	30 mn-50%-75%	5.91	8.45	21.99	9.70	9.71	1.58	35000	23.70	5181	5270	1.46.E+07	-1.46.E+07	1.33.E+05	110.13	2.04	3.70
	60 mn-25%-50%	3.04	8.46	21.85	9.71	4.03	6.25	35000	23.60	5320	0	2.71.E+07	-2.70.E+07	2.34.E+05	115.79	2.06	3.60
	60 mn-50%-75%	6.42	8.45	21.99	9.70	4.63	2.14	35000	23.70	5486	5749	1.21.E+07	-1.21.E+07	1.15.E+05	105.64	2.02	3.70
	120 mn-25%-50%	6.53	8.45	21.99	9.70	7.30	2.07	35000	23.70	5626	5801	1.42.E+07	-1.42.E+07	1.11.E+05	128.09	2.11	3.70
	120 mn-50%-75%	6.87	8.40	22.39	9.64	10.88	1.68	35000	24.00	5801	6221	1.59.E+07	-1.59.E+07	9.70.E+04	163.48	2.21	4.00

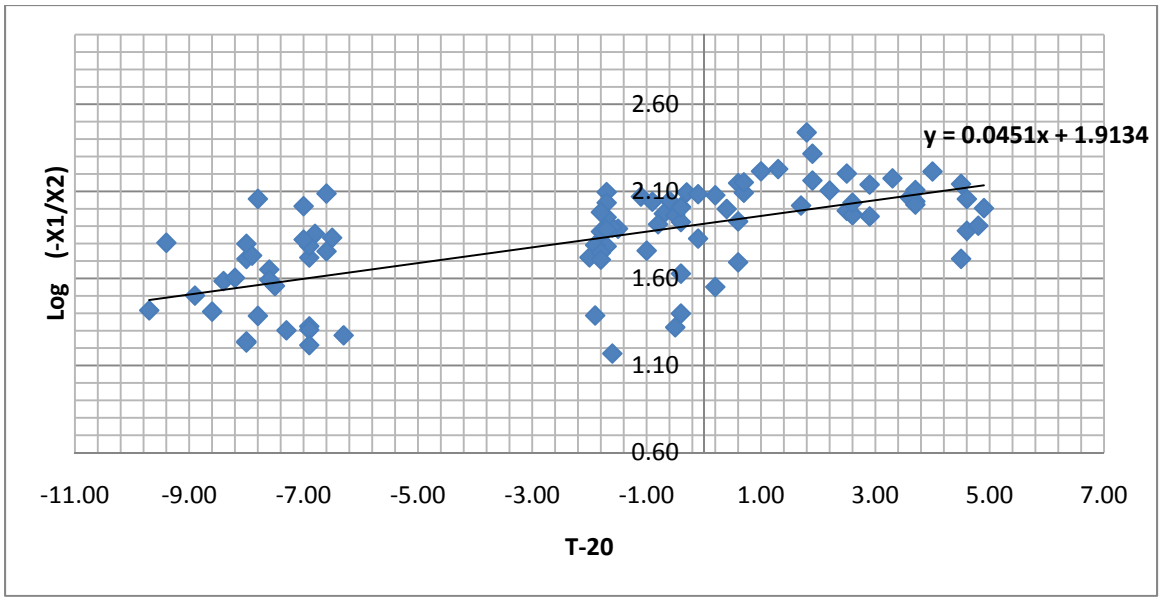


Figure 4.22: Plot of data fitted to Equation 4.11

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

The following are the conclusions reached after analyzing the results of this research in the LRWRP BAF:

1. A low nominal airflow rate 1300 m^3/hr is sufficient for NH_3 and BOD removal from the BAF wastewater.

2. Most of the BOD removal was within first 25 % of the cell at 1700 m^3/h nominal air flow rate, and the removal was constant with depth at 1300 m^3/h nominal air flow rate.

3. BOD removal is mainly dependent on airflow to water flow ratio, temperature and BOD concentration of inflow wastewater in the BAF. With a specific water flow rate the lower airflow rate gives a better BOD removal efficiency in the BAF.

4. Ammonia removal is independent of airflow in this BAF. Ammonia removal capacity depends on ammonia loading between 1300 m^3/h to 1700 m^3/h airflow rate. Most of the ammonia was removed with in the first 50% for both the 1300 m^3/h and 1700 m^3/h nominal airflow rates.

5. The possible causes of the imbalance between ammonia consumed and nitrate produced are that nitrogen is being fixed in cell biomass, and denitrification.

6. The re-aeration coefficient was 1966/d for the BAF in LRWRP.

5.2 Future recommendation

Further studies be continued at lower nominal airflow rate below 1300m^3/h to find the lowest airflow rate which will provide sufficient ammonia and BOD removal in the BAF. VSS can be determined by taking a composite sample of the backwash and analyzing that to confirm the calculated yield in the LRWRP.

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APPENDIX A

Nitrogen mass balance Calculations

Inflow									
Month	SS (mg/L)	VSS (mg/L)	N (mg/L)	CBOD (mg/L)	COD from BOD (mg/L)	TKN (mg/L)	(NO_3+NO_2) (mg/L)	Soluble-N (mg/L)	Total- N (mg/L)
February, 2010	25.68	20.33	2.52	30.50	172.33	13.50	0.76	14.26	16.78
March, 2010	33.14	26.23	3.25	31.00	175.15	15.16	1.25	16.41	19.66
April, 2010	29.13	23.06	2.86	30.77	173.85	13.39	1.02	14.41	17.27
May, 2010	40.63	32.17	3.99	34.64	195.73	13.55	0.86	14.41	18.40

outflow									
Month	SS (mg/L)	VSS (mg/L)	N (mg/L)	CBOD (mg/L)	COD from BOD (mg/L)	TKN (mg/L)	(NO_3+NO_2) (mg/L)	Soluble-N (mg/L)	Total- N (mg/L)
February, 2010	14.87	11.77	1.46	6.80	38.42	5.52	3.70	9.22	10.68
March, 2010	16.14	12.78	1.58	8.84	49.94	6.01	3.89	9.90	11.48
April, 2010	15.10	11.95	1.48	3.20	18.08	4.57	4.19	8.76	10.24
May, 2010	17.97	14.22	1.76	5.53	31.26	4.48	3.78	8.26	10.02

Month	Δ COD (CBOD is with SS) (mg/L)	NFixed(CBOD is with SS) (mg/L)	ΔTotal N(CBOD is with SS) (mg/L)	N_2 (g) (mg/L)
February, 2010	133.9	6.48	6.10	-0.37
March, 2010	125.2	6.06	8.18	2.12
April, 2010	155.8	7.53	7.03	-0.51
May, 2010	164.5	7.95	8.38	0.42

Where,

N (mg/L) = VSS (mg/L) x 0.124

Soluble N (mg/L) = TKN (mg/L) x (NO3+NO2) (mg/L)

Total N (mg/L) = Soluble N (mg/L) + N (mg/L)

Δ COD (CBOD is with SS) (mg/L) = COD from BOD (mg/L) - COD from BOD (mg/L)

N_{Fixed} (CBOD is with SS) (mg/L) = Δ COD (CBOD is with SS) (mg/L) x 0.124 x Yield (VSS/COD)

ΔTotal N (CBOD is with SS) (mg/L) = Total N $(mg/L)_{in}$- Total N $(mg/L)_{out}$

$N_{2\,(g)}$ (mg/L) = ΔTotal N(CBOD is with SS) (mg/L) - N_{Fixed} (CBOD is with SS) (mg/L)

Nitrogen content in VSS: amount of nitrogen in cell biomass = g N/g $C_5H_7NO_2$

=14/ (60+7+14+32)

=0.124

=12.4%

N mass balance in the cell

$N_{in},T = N_{fixed} + N_{out},T + N_2$

Therefore,

$N_{in},T - N_{out},T = N_{fixed} + N_2$

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