Enhanced Microbial Activity and Energy Conservation through Pneumatic Mixing in Sludge Systems

By

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ABSTRACT

The primary goal of this study was to evaluate a new device and system, designed to optimize the performance of standard low pressure air diffusers in two types of aerated systems (activated sludge and aerobic sludge digestion) and to decrease overall energy consumption.

Aerated treatment systems are very important in the treatment of wastewaters and management of sludges. The activated sludge process is widely used to treat wastewater from both industrial and municipal sources. However, they are costly to operate because oxygen is marginally soluble in water and standard low pressure (8 psig) diffusers provide marginal mixing and minimum retention.

The newly patented device is referred to as TotalMix and is a type of pneumatic mixing system. TotalMix introduces air under high pressure at regular fixed intervals. During the tests the frequency of air delivered, the pressure, and the period of pressured air delivery was varied manually or through feedback control to optimize oxygen transfer and the interaction with a regular aeration system. Various chemical parameters, most importantly dissolved oxygen, were measured and compared to the new approach, using the TotalMix in combination with standard diffuser systems.

The new System was tested in different sized tanks (17,000 L and 380,000 L), different concentrations of total solids (TS), using different airflow rates and different diffusers (membrane fine bubble diffusers, ceramic fine bubble diffuser, and course bubble diffuser). The statistical evaluation of the experiments indicates an increase in oxygen transfer rate with a concomitant decrease in energy consumption at low airflow rates.

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Introduction

Aeration is an important step in wastewater treatment at which air is added to wastewater for mixing purposes and to provide an aerobic environment for microbial degradation of organic matter. The microbes use the oxygen as an energy source to break down the complex organic structures. With oxygen being only slightly soluble in water, its transfer must be engineered into the treatment unit. The first basic experiments in aeration technology were conducted as early as 1882 (Martin 1927), but real improvements started with the work of Arden and Lockett in 1914, who focused on the importance of bubble size, diffuser placement, tank circulation and gas flowrate on oxygen transfer efficiency (Boyle 2002).

To this day, aeration systems are an important but costly requirement for normal activated sludge plant operation and may comprise 40-80% of the energy cost of operating a treatment plant (Bischof et al. 1996; Stenstrom and Boyle 1998). It is easy to see that the proper design of wastewater treatment plants has become more and more important, yet until 1983 information about how to design and operate aeration systems was scarce. However, the development of the ASCE Clean Water Standard (1983, 1991), U.S. EPA's fine pore diffuser handbook (1989), and the ASCE Standard Guidelines for In-Process Water Testing (1996) have helped answer important questions related to the design more efficient aeration systems (Stenstrom and Boyle 1998).

Today, two types of aeration systems are most commonly used: subsurface and mechanical (Solomon 1998). Mechanical systems introduce air from the atmosphere into the wastewater by agitating it by various means (e.g. propellers, blades, or brushes), while subsurface systems release air by diffusers (course or fine bubble) or other devices submerged in the wastewater. Although both systems introduce air into the wastewater, the air bubbles differ in sizes due to the different aeration systems. Generally, bubbles are considered fine when their diameters are less than 5 mm, whereas coarse bubbles may have diameters as large as 50 mm (Rosso and Stenstrom 2006). More specifically, coarse and fine bubble diffusers have been identified based on their oxygen transfer efficiency (OTE). The bubble surface area of smaller bubbles is greater per unit volume, which results in a greater OTE, which in turn makes fine bubble diffusers more effective for wastewater treatment plants (Solomon 1998). Tests conducted by Höfken (1996) showed that the maximum oxygen input is achieved with gas bubbles of 1.6 mm to 1.9 mm (Figure 1).

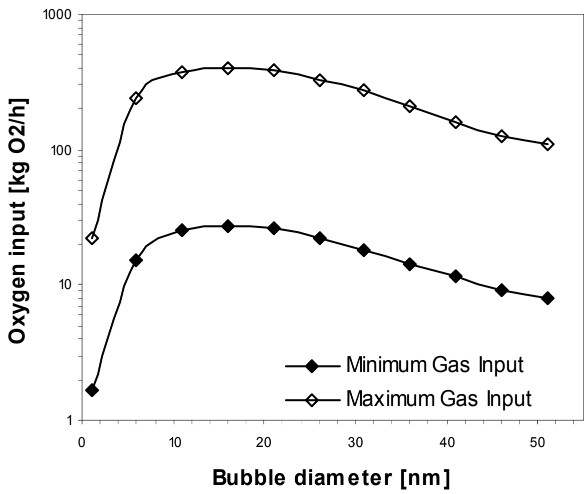


Figure 1: Oxygen input with gas bubbles of uniform size (adapted from Bischof et al. 1994)

In the late 1980's many wastewater treatment plants upgraded their aeration basins with fine bubble diffusers and therewith decreased their energy costs (Stenstrom 1990). However, fine bubble diffusers have historically been associated with clogging and maintenance problems (EPA, 1985), which led to the development of other aeration equipments, such as submerged turbines or jet diffusers. This systems create fine bubbles without the help of small orifices (Rosso and Stenstrom 2006) and are less prone to clogging and require less cleaning time.

Although, there has been improvement in the clean water performance tests since the 1970s, there are still problems to be solved. One critical step in the design of aeration systems is the translation of clean water oxygen transfer rates to field conditions (Doyle et al. 1986). Another is the interaction of wastewater constituents with diffuser materials, in terms of efficiency, maintenance and mixing ability.

1. Different Aeration Systems

The common goal of the various aeration systems available on the market is to distribute air into the wastewater as uniformly and economically as possible. Diffusers are the active and the most essential elements of an aeration system. Their design, geometric dimensions and pore sizes define the efficiency of the aeration process with respect to the dissolved oxygen. The technical designs available vary widely ranging from porous, solid designs to elastic, perforated materials (Bischof et al. 1996). Diffusers are placed close (ca. 15 cm) to the tank bottom where they release bubbles traveling towards the tank surface. The space below the diffuser, where no dispersion occurs, is prone to sedimentation of the particles and needs to be cleaned regularly (Figure 2).

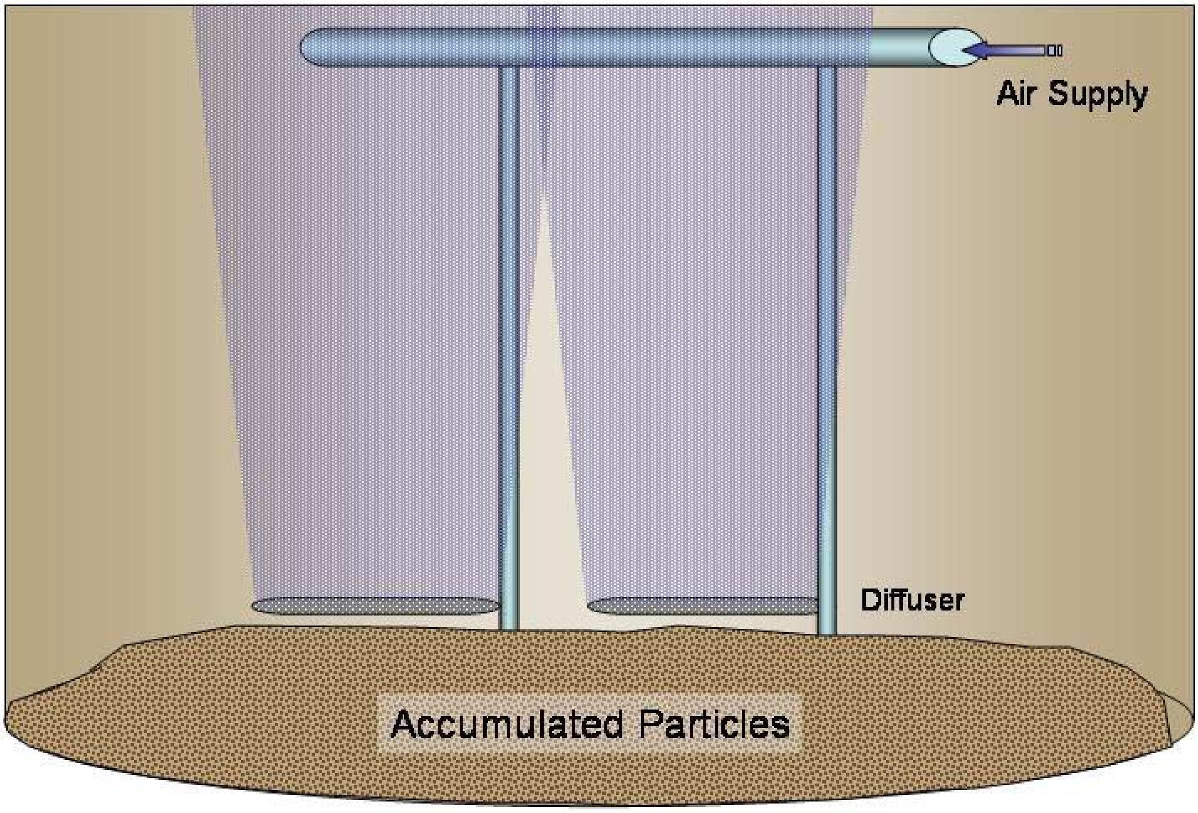


Figure 2: Mode of operation of a standard diffuser system with accumulated particles below diffusers

A great variety of diffusers are available. The porous, solid diffusers release air through labyrinth-type porous material (plastic-coated quartz sand, sintered metals, plastics, and ceramics). The most efficient types are fine bubble diffusers, which are usually made from ceramics, plastics, or flexible perforated membranes, and have different shapes (discs, tubes, domes, and plates). Ceramic media diffusers have been in use for many years due to cost considerations and have essentially become the standard for comparison (EPA 1999). Within recent years, membrane fine bubble diffusers have become of more interest due to their higher oxygen transfer efficiency. Advantages of membrane fine bubble diffusers are a significantly lower investment price and a better adaptation of the air flowrate (Libra et al. 2005). The disadvantage of fine bubble systems is the lower mixing capability of the diffused air and that water carrying dirt and particles in suspension can enter the porous structure at intermittent flowrates and possibly leading to clogging of the pores (Bischof et al. 1996). The simplified sketch in Figure 2 shows that mainly the area directly above the diffuser is aerated, resulting in pockets with low to zero DO concentration in the tank further away from the diffusers. This effect is enhanced at lower to intermittent airflow rates. Although elastic materials are less affected by intermittent operation, as their smooth surface and elasticity properties prevent deposition and clogging, they still require higher maintenance than coarse bubble diffusers (Höfken et al. 1996). A further aspect to consider is the longevity of membrane diffusers in contrast to solid diffusers. A three year study, comparing ceramic and membrane diffusers indicated that the initial, higher standard-oxygen-transfer efficiency and standard-aeration efficiency of membrane diffuser decreases over time, while ceramic diffusers started at a lower efficiency, but increased slightly over the whole period (Libra et al. 2005) and could be more economical for a treatment plant in the long run. Other disadvantages of fine pore diffusers, especially for perforated membrane types, are that they may be susceptible to chemical attack and thus be inadequate for some types of wastewater. More importantly the required airflow may be dictated by mixing – not by oxygen transfer (Solomon 1998).

For aeration systems, mixing is an often overlooked aspect of lowering the costs of dissolved oxygen distribution. Typically, meeting the biological oxygen demand (BOD) is the predominant concern for wastewater treatment facilities during the day, but with decreasing BOD loads during the late evening hours, adequate mixing in the tank may be the controlling energy requirement (EPA 1999). Typical minimum mixing values for different aeration systems are shown in Table 1.

Table 1: Typical Aeration Tank Mixing Requirements (Metcalf and Eddy 1991)

Aeration System	Mixing Requirement
Course Bubble Diffused Aeration	570 to 850 L/min/28.3 m^3
Fine Bubble Diffused Aeration	200 to 280 L/min/28.3 m^3
Mechanical Surface Aeration	447 to 858 W/28.3 m^3

Above mentioned mixing requirements vary in aerobic digesters with high suspended solids concentration. Experiments showed that it is difficult to maintain aerobic conditions throughout an aerobic digester. Several researchers have indicated that the decay rate of waste solids declines with increasing solids concentration and believe that the increasing difficulty of transferring oxygen and maintaining aerobic conditions throughout the digesting solids particles is the reason.

The assessment of different aeration designs and the determination of which system is the most efficient for a treatment plant is generally based on identifying the quotient of oxygen supplied and the energy required, the so called yield or power efficiency (Liu 2004). Typical clean water oxygen transfer rates range from 1.2 kgO_2/kWh for course bubble diffusers to up to 3.9 kgO_2/kWh for fine bubble diffusers (EPA 1984). Including gas transfer rate is especially important when compressed air is used, because it strongly influences the buoyancy of the plume (Wuest 1992). Early work on coarse and fine bubble aeration systems also revealed impacts on OTR due to geometry and density effects, it also showed that aerators, spreading air across the basin floor as much as possible had the greatest transfer efficiencies (Stenstrom 1996).

The TotalMix system utilizes this fact and introduces high pressure air to mixed liquor or sludge, resulting, in greater and more homogeneous DO concentrations. Preliminary tests showed that the high bursts of air move at first in a horizontal direction, parallel to the tank floor and extend to as much as 46 cm from the nozzle face. The detected bubble sizes created by the TotalMix head range from the size of BB's to softballs.

The gas-water plume mixture is less dense than the ambient wastewater, which causes the mixture to ascend and to entrain ambient wastewater into the plume which increases its width (Singleton 2007). The bubble array covers approximately 0.13 m^2 at the tank bottom before buoyancy push outwardly to form a cone-shaped configuration. At a height of about 5.2 m the bubbles form an expanded cone of 10 to 20 times (up to 2.6 m^2.) its original area. The expanding cone impacts the diffused air by retaining the bubbles within the turbulence. Therefore, this increases the retention time of diffused air bubbles and will therefore significantly reduce the requirements of the continuously-operated, diffused air system. The sketch in Figure 3 demonstrates the mode of operation of the TotalMix head

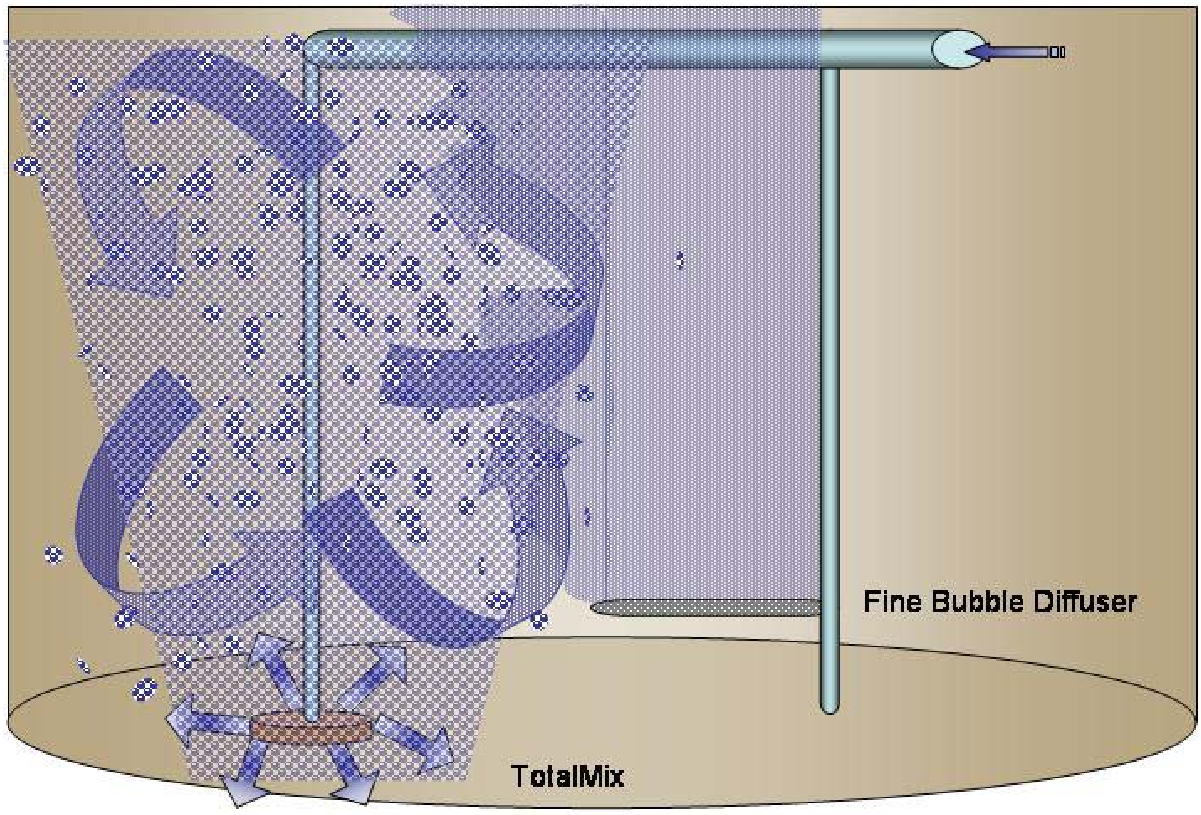


Figure 3: Mode of operation for the TotalMix / diffuser combination

Another aspect is the fact that OTR tends to decrease with increasing airflow due to the increasing headloss (Iranpour 2001).The amount of oxygen that can be supplied depends on the range of the bubble sizes generated, the oxygen content in the bubble during generation, the original oxygen content in the water, the content of other gases like CO_2 in the water, water depth, water temperature, and the extent to which the water is contaminated with surfactants (Bischof et al. 1996).

2. Evaluation of Aeration Systems

2.1. Theoretical background

The most important purpose of aeration systems is the transfer of oxygen to biological-treatment processes. Oxygen solubility is a function of several factors: temperature, dissolved solids concentrations, liquid depth, the partial pressure, and the diffuser type (Eckenfelder 1966).

Gas transfer into a liquid phase is usually described with the “Two Film Theory” (Lewis and Whitman 1924). In this theory the existence of two thin films on each side of the interface form the basic concept. Gas molecules must slowly diffuse through those two films in order to dissolve into the liquid phase. The driving force is defined by Henry’s Law, the concentrations of dissolved gases are at equilibrium with the gas phase. Due to turbulent mixing, the gas film concentration in the bulk liquid is uniform at all points. The liquid film, on the other hand, is free from turbulence and transfer across the films at steady state conditions can be assumed.

Two methods exist to test the oxygen transfer rate and overall efficiency of aeration systems in wastewater facilities. Steady state conditions (completely-mixed systems) do not reflect the reality in wastewater treatment units and, therefore, the unsteady-state techniques are more commonly used to evaluate the efficiency of an aeration system. In this study, the rate of change of dissolved oxygen concentration was measured during reaeration of deoxygenated clean water.

2.2.Oxygen Transfer Rate (OTR)

In order to identify the most efficient aeration system, it is important to be able to compare different aeration systems. The parameters used to assess the efficiency of the equipment are K_{La} and the Standard Oxygen Transfer Rate (SOTR). The OTR is the value obtained under test conditions; it describes how much oxygen is dissolved per hour in clean water at 0 mg/L dissolved oxygen. After normalizing the data for standard conditions, we use the Standard Oxygen Transfer Rate (SOTR). K_{La} is defined as volumetric mass transfer rate coefficient, and SOTR is the mass of oxygen transferred under standard conditions per unit power into the aeration equipment. Ultimately the yields will be compared. This is the quotient of oxygen quantity supplied and the energy required.

2.2.1. Determining of OTR

a) Gas Transfer in Clean Water

Gas transfer may involve either the adsorption or desorption of gas. Aeration kinetics can be expressed as:

$$\frac{dC}{dt} = K_{La}(C_s - C) \qquad (1)$$

Where,

C_s = saturation level of oxygen [mg/L]
C = actual oxygen concentration [mg/L]

K_{la} = overall transfer coefficient [1/hr]

Integrating the equation, then we receive:

$$K_{La} = 0.203 \cdot \frac{1}{(t_1 - t_0)} \cdot \log\left(\frac{(C_s - C_0)}{(C_s - C_1)}\right) \tag{2}$$

Where,

C_0 and C_1 are the dissolved oxygen levels at observed times t_0 and t_1.

K_{La} values should be reported at 20°C and 1 atm pressure, in order to compare different aeration systems. K_{La} at 20°C can be calculated by using Equation (3).

$$K_{La}(20°\mathrm{C}) = \mathrm{K}_{\mathrm{La}(T)} \Theta^{(20-T)} \tag{3}$$

Where,

T = Temperature at which K_{La} is determined
θ = Temperature correction factor (1.024 for clean water)

b) Gas Transfer in Wastewater

Being the overall transfer coefficient, K_{La} for a gas changes with variations in the physical and/or chemical properties of the solution. Those changes can be described by the introduction of α and β coefficients. The α coefficient is defined as the ratio of the K_{La} value for wastewater to the K_{La} for clean water:

$$\alpha = \frac{K_{La}(Wastewater)}{K_{La}(Clean Water)} \tag{4}$$

Usually, α values are less than 1, but change during treatment, and approach unity for treated wastewater, since the substances affecting the transfer rate are being removed in the process. Table 2 summarizes reported α values for different aeration devices.

Table 2: α - Values for different aeration devices (EPA 1989)

Aeration device	Alpha factor
Fine bubble diffuser	0.45
Coarse bubble diffuser	0.8
Jet Aeration	0.75

β is defined as the ratio of the oxygen saturation level for a wastewater to the oxygen saturation level for clean water.

$$\beta = \frac{C_s(Wastewater)}{C_0(CleanWater)} \tag{5}$$

Introducing α and β values into equation (2) we obtain:

$$\frac{dC}{dt} = \alpha \cdot K_{La}(\beta \cdot C_s - C) \tag{6}$$

During steady-state operations, $\frac{dC}{dt}$ equals zero. The rate of oxygen transfer is constant and equals

$$r_{O_2} = \alpha \cdot K_{La}(\beta \cdot C_s - C) \tag{7}$$

If large quantities of sodium sulfate (Na_2SO_3) are added to reach steady-state, then the oxygen concentration, C, is zero and

$$r_{O_2} = \alpha \cdot K_{La}(\beta \cdot C_s) \tag{8}$$

2.2.2 Impact of Airflow rate on OTR

An increased aeration rate, resulting in a high throughput operation, generates a high crossflow velocity which minimizes fouling in submerged membrane bioreactors (Howell et al. 2004). In clean water, a higher airflow rate results in a decreased oxygen transfer efficiency, due to an increase in the bubble size (Gillot 2000). The increased bubble sizes are caused by

a) stretching of the membrane as an effect of the gas pressure (Rice 1987), and
b) an increase in the coalescence of the air bubbles (Calderbank 1964).

Higher airflow rates also affect the vertical movements of the liquid. These vertical flows from the diffuser to the liquid surface accelerate the upward velocity of the air bubbles and are greater when the airflow rate is increased (Roustan 1996), leading to a reduced bubble retention time and to less efficient oxygen transfer (Gillot 2000). Under process conditions, the OTR also decreases with higher airflow rates. However, this does not always match the clean water values, leading to a variation in the alpha factor (Gillot 2000).

3. Objectives

Reliable and cost-effective processes are required for treating municipal wastewater. New regulations (higher discharge quality, better nutrient removal) put pressure on reducing energy consumption in wastewater treatment plants (Libra et al. 2005). Therefore, there are strong incentives to upgrade existing wastewater treatment plants in order to be better prepared for the future effluent standards and also to save energy costs (Chachuat et al. 2005). One step into this direction was the replacement of coarse bubble diffusers through fine bubble diffusers, which reduced the aeration costs but still remains the main cost factor of a wastewater treatment plant. The performance of the aeration system will critically affect plant economics and this not only includes aeration efficiency and energy consumption but also their life span and maintenance. In this study the efficiency of a new aeration/mixing system was investigated using full scale and pilot scale experimental systems. The main objectives of this research were to evaluate a) the aeration efficiency and b) the energy consumption of the new mixing device when combined with a standard diffuser.

Materials and Methods

1. Description of Field Experiments

The new mixing device was tested at two different sites. Pilot scale experiments (17,000 L) were performed at the Pepper's Ferry wastewater treatment plant in Radford, Virginia. Tests under full-scale conditions (380,000 L) were conducted in Conway, South Carolina.

1.1. Full-Scale System, Conway, SC

Initial experimental setup and testing took place in early July 2006 and continued through August 2006. The testing site was located at the High Tech Turf Farm in Conway, South Carolina. At the turf farm, Class B biosolids were land-applied after being aerated in six cylindrical tanks, that each held approximately 380,000 L of sludge. Each of the tanks (*Fisher Tank Company, Lexington, SC*)was 10.4 m in diameter, 4.9 m tall and filled with ca. 1.3% TSS sludge from the Schwartz Wastewater Treatment Plant.

The tanks were each equipped with a 5 hp blower powering 26 coarse bubble diffusers. The diffusers were located 0.3 m above the tank floor in two rows. Each row, consisting of 13 diffusers, was positioned 2.7 m from the center (Fig. 4). For this research project, only one tank was used. The aeration tank was modified by retrofitting TotalMix into the tank. TotalMix was placed 0.3 m way from each diffuser towards the tank wall. Additionally TotalMix systems were installed perpendicular to the diffusers (Fig. 4). Every set of TotalMix systems was connected to a solenoid valve and programmed to release air bursts in sequence to maximize the turbulence.

Sampling beams were only placed on one half of the tank since the tank's aeration was installed symmetrically. It could therefore be assumed that the aeration pattern on the other half of the tank was the same this way, the sampling time was decreased, which allowed for a comparison of data points from each beam. Measurements were taken on each sampling beam (Fig. 5) at three different depths (0.6, 1.8, and 3.7 m) and different widths (1.2, 4.3 and 7.3 m) alternating between the diffusers alone and the diffuser/TotalMix combination.

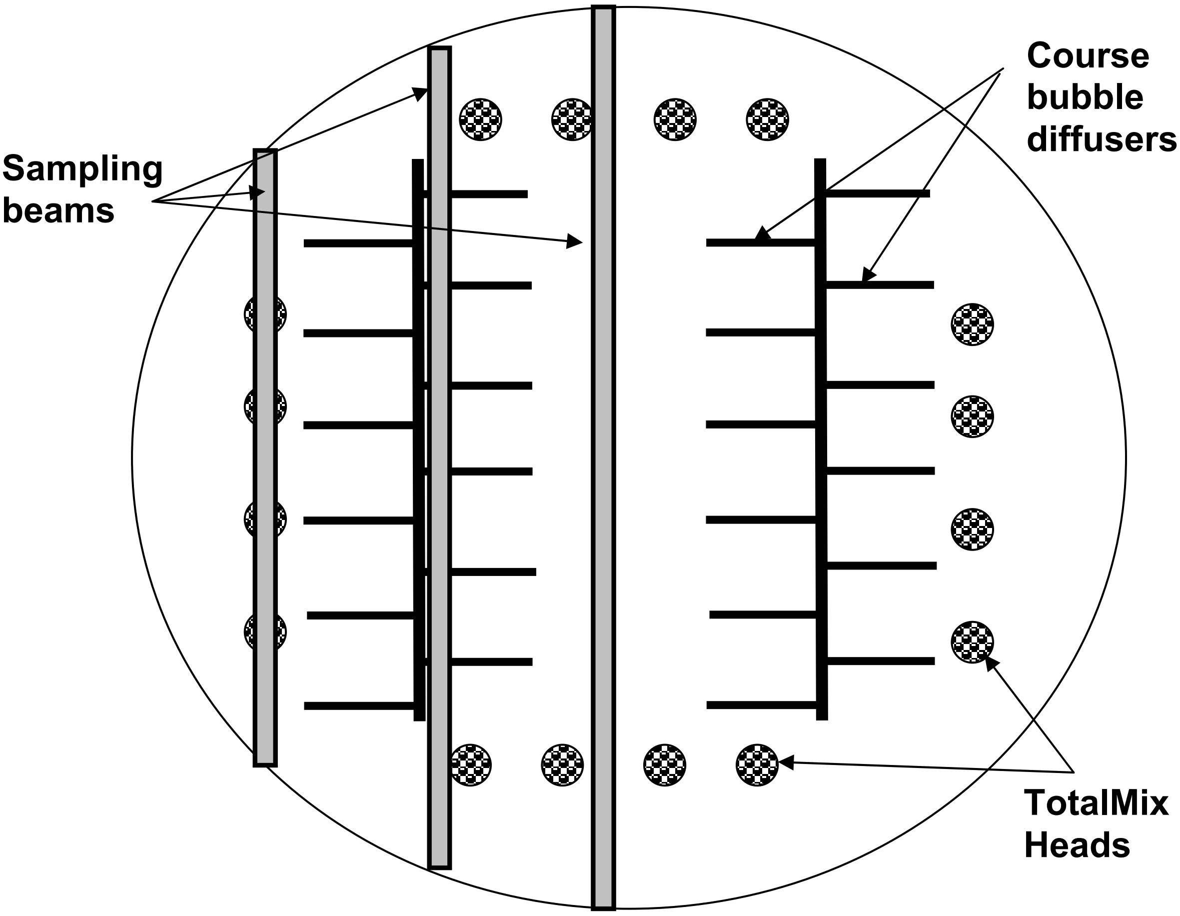


Figure 4: Schematic Experimental Set-Up in full-scale tank

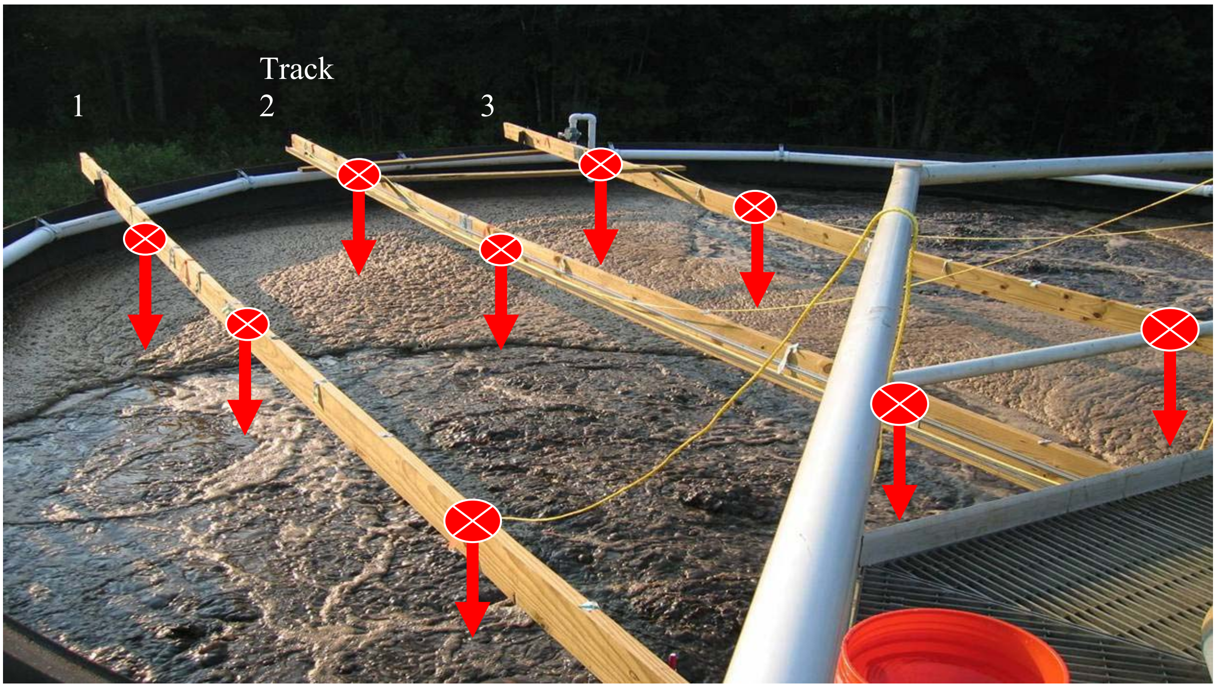


Figure 5: Overview of the sampling points in the full-scale tank.

1.2. Pilot-Scale System, Radford, VA

To test different diffusers and wastewater suspensions, a pilot-scale system with a 17,000 L tank (3.7 m high) was set-up at the Pepper's Ferry Wastewater Treatment Plant in Radford,VA. The tank was equipped with one TotalMix head placed in the center of the tank and one diffuser located ca. 0.6 m towards the tank wall (Fig. 6).

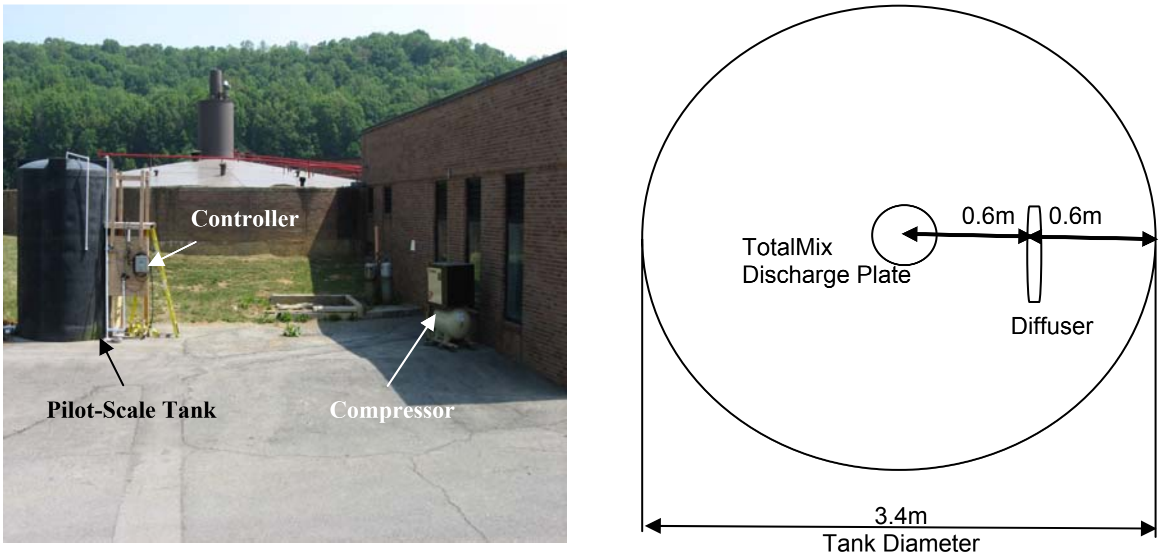


Figure 6: Experimental Set-Up at Pepper's Ferry Wastewater Treatment Plant, Radford, VA.

The wastewater types tested included activated sludge, thickened activated sludge, and treated effluent (used for clean water testing). The diffusers considered were ceramic and membrane diffusers. The activated sludge was taken from a clarifier; the thickened activated sludge was taken after a dissolved air flotation unit (DAF), and the water for the clean water tests was taken from the plant's effluent.

2. Materials

2.1. TotalMix System

2.1.1 Description

The newly patented device is referred to as TotalMix and is a type of pneumatic mixing system (Fig.7). The programmable and intermittent high pressure mixing system has never been used in wastewater treatment applications.

Figure 7: TotalMix discharge plate

The bottom plate of the disk-shaped mixing device has a 30.5 cm diameter and is 1.3 cm thick. The plate is separated into 6 equal wedges (50°) which are placed 5 cm. apart from each other (Fig. 8).

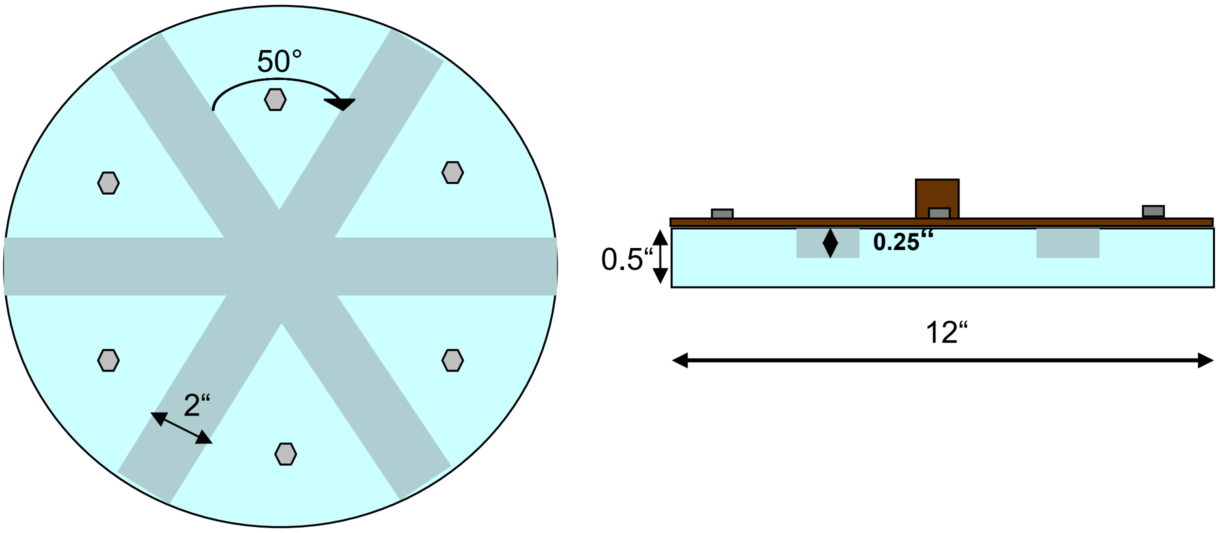


Figure 8: Dimensions of the bottom plate of the pneumatic aeration device (TotalMix)

Six bolts hold the bottom plate to the metal top. The metal plate, with the standard 1.9 cm (¾ inch) pipe thread allows for an easy retrofit. Furthermore, the systems benefits include that the high pressure prevents the canals from clogging and keeps it clean. Also compared to standard diffusers, which are located about 15 cm above the tank bottom, the TotalMix head is placed about 2.5 cm above the tank bottom, which has the advantage that particles are kept in suspension and cannot accumulate below the diffusers.

2.1.2 Pilot-Scale Tank

The disk-shaped mixing device was located 2.5 cm above the basin floor and ca. 13 cm below the diffusers. Air was introduced under a pressure of about 2,800 hPa. The period of pressured air delivery was varied manually, but can also be changed through feedback control to optimize oxygen transfer and the interaction with a regular aeration system (ceramic or membrane diffusers). The piping from each frame was connected to a solenoid valve, which was operated by a programmable time-sequence controller (Fig. 9).

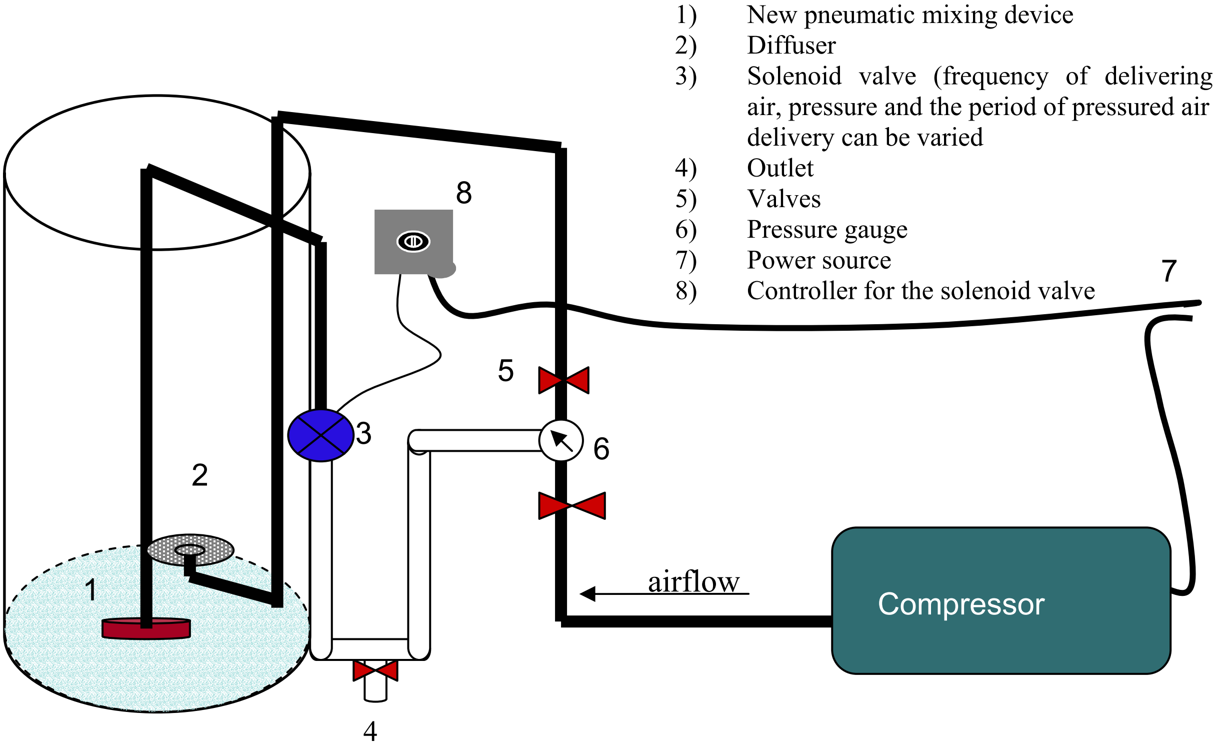

1) New pneumatic mixing device
2) Diffuser
3) Solenoid valve (frequency of delivering air, pressure and the period of pressured air delivery can be varied
4) Outlet
5) Valves
6) Pressure gauge
7) Power source
8) Controller for the solenoid valve

Figure 9: Experimental Set-Up in 17,000 L tank

The materials shown in Figure 9 are described in more detail in Table A1 of the Appendix.

2.2. Compressor, Controller, and Valves

The same rotary contact cooled compressor, UNI 15TAS (*Ingersoll-Rand Company, Davidson, NC*) was used for the pilot-scale as well as for the full-scale experiments. The valve controlling the air burst times at both field sites was connected to an Allen-Breadely PICO/GFX-70 controller (*Rockwell Automation Global Headquaters, Milwaukee, WI)* that included PicoSoft Pro Software. Four 2-way solenoid valves (*MAC valves,Wixom, MI)* were used for the full-scale tank and one of those valves was used for the pilot-scale tank

2.3. Diffusers

Oxygen transport is a complex process depending on a variety of factors, amongst others, the type of diffusers. To evaluate the most efficient set-up, we tested a membrane diffuser and a ceramic diffuser.

2.3.1 FlexLine Nonbuoyant Tubular Diffuser (*Siemens, Waukesha,WI)*

The FlexLine Nonbuoyant Tubuluar Diffuser (Fig. 10) increases the bubble surface contact area with water by producing microfine bubbles. A bigger surface contact area results in an increase in oxygen transfer efficiencies and ultimately in lower air volume requirements. Higher transfer efficiencies will lower energy costs and improve effluent quality. While other diffusers emit a narrow column of air, the FlexLine diffuser produces a broad envelope of bubbles that greatly increases transfer efficiency and improves mixing.

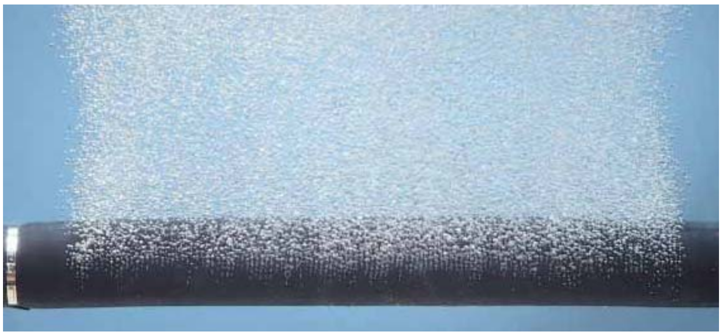


Figure 10: LexLine Nonbuoyant "Tubular Diffuser (photo by Siemens)

The FlexLine diffuser is open at both ends, so the water can fill the tube completely when airflow is off. The filled tube eliminates buoyancy and bounce that weakens joints and causes leakage. Also, with no airflow, the membrane contracts and seals off the distribution chamber, eliminating a chance of backflow. On the other hand, when airflow is on, the sleeve inflates around the exterior of the support tube and creates air distribution over the entire membrane surface. As a result, a larger perforated surface area greatly increases transfer efficiency. The biggest advantage of the FlexLine diffusers is the length. They are 60 cm long and have 8400 bubble producing 'I' slits. This set-up allows flow ranges up to 200 L/min, while still maintaining high oxygen transfer efficiencies and keeping the headloss low.

2.3.2 Ceramic Fine Bubble Diffuser (*Diffused Gas Technologies, Inc., Lebanon,OH)*

Ceramic fine bubble diffusers (Fig. 11) are commonly used in environments which require aeration in extreme duty applications. The Ceramic Dome diffuser introduces the gas between the dome and its base. The gas permeates throughout the porous labyrinth of the dome and migrates through the minute passages of the dense ceramic matrix structure. When the gas reaches the surface of the dome, it creates a surface tension between the gas and the liquid. A minute bubble is formed once the surface tension is overcome. The ceramic diffuser operates at flow ranges up to 70 L/min.

Figure 11: Standard Ceramic Fine Bubble Diffueser (http://www.diffusedgas.com/page6.html)

2.3.3 Coarse Bubble Diffuser

These wide band diffusers (Fig. 12) are typically used in high rate, conventional and extended aeration activated sludge processes. They achieve wide band aeration due to their reach of 122 cm perimeter. The diffusers have an air reservoir and dual horizontal levels of diffusion ports on the diffuser sides, which assures uniform air distribution. (*http://www.sanitaire.com/pdf/brochures/CoarseBubble.pdf*)

Figure 12: Standard Coarse Bubble Diffuser (picture by Environmental Dynamics Inc.)

2.4 Analytical Equipment

2.4.1 YSI 6820 and 650MSD (*Yellow Springs Instruments, Yellow Springs, OH*)

The YSI 6820 is a multi probe (Fig. 13) that allows for several measurements simultaneously (NO_3^-, NH_4^+, Dissolved Oxygen, Conductivity, Oxidation Reduction Potential, pH and Temperature). The waterproof 650MSD (Multiparameter Display System) (Fig. 12) logs real-time data, calibrates YSI 6-series sondes is the handheld that logs real-time data, calibrates theYSI 6820 probe, and uploads data to the computer. Initially, a membrane dissolved oxygen probe was used but the membrane deteriorated too quickly in the activated sludge so an optical dissolved oxygen probe was used instead. This probe measured the dissolved oxygen in percentage, from which mg/L of DO was calculated.

Figure 13: YSI multi probe 6820 and the 650MSD Handheld logging device (Photos: YSI)

The YSI optical sonde covers a range from 0 to 50 mg/L with a resolution of 0.01 mg/L.

2.4.2 Advanced Hach (*Hach, Loveland, CO*) LDO® Process Dissolved Oxygen Probe

The HACH LDO dissolved oxygen probe (Fig. 14) applies new luminescence technology to continuously monitor dissolved oxygen. The instrument can be used effectively in a range of applications (aeration tanks, nitrification and denitrification tanks, aerobic and anaerobic digesters, etc.).

Figure 14: LDO Dissolved Oxygen Probe with sc 100 Universal Controller (Photo: Hach)

Mode of operation:

The sensor is coated with a luminescent material. The sensor surface transmits blue light from an LED, which excites the luminescent material. As the material relaxes it emits red light. The time between the blue light is sent and the red light is emitted is measured. This time is proportional to the amount of dissolved oxygen present in the tested wastewater. The more oxygen is present the shorter the time until the red light is emitted. Between the flashes of blue light a red LED is flashed on the sensor and is used as an internal reference.

The instrument is capable of measuring a DO range of 0.00 ppm to 20.00 ppm with a resolution of 0.01 ppm and a response time of < 30 seconds for wastewater.

3. Methods

Tests were performed in aerated tanks using different types of wastewater, different types of diffusers, and different flow rates. In these tests, measurements of various parameters were recorded over time (Table 3). Measurements were taken with a YSI Model 6820 (Yellow Springs Instruments, Yellow Springs, OH) and recorded via EcoWatch Software (YSI) program. For each test, TotalMix pressure, the diffuser pressure, the total suspended solids (TSS) concentration, and the chemical oxygen demand (COD) were measured and recorded

Table 3: List of Measured Parameters

Field Test	
	Dissolved Oxygen (DO)
	Ammonia – N (NH_3-N)
	Ammonium – N (NH_4^+-N)
	Nitrate – N (NO_3 – N)
	pH
	Conductivity
	Oxidation – Reduction Potential (ORP)
	Temperature

Laboratory	
	Chemical Oxygen Demand (COD)
	Total Suspended Solids (TSS)
	Volatile Suspended Solids (VSS)

Total suspended solids (TSS) and volatile suspended solids (VSS) were analyzed using Method 2540D and 2540E, respectively (Standard Methods, 1995). The total and soluble chemical oxygen demand (TCOD and SCOC) were measured based on method 5220C (Standard Methods, 1995).

All field tests were carried out alternating between standard diffuser systems and the combination of diffusers with the TotalMix System. Different diffusers, the optimum time setting, different types of wastewater, different airflow rates and the energy consumption of the different systems were evaluated in the pilot-scale tank. In the full-scale tank the efficiency of the TotalMix system was compared to the standard aeration system to collect real-world data. Table 4 provides a summary of the tests performed and Figure 15 gives an overview of the different airflow rates used in the respective wastewater and diffuser. For the clean water tests, measurements of dissolved oxygen (DO) were recorded over time in a solution where oxygen was first depleted with sodium sulfite. Based on Viessman (2005), 7.88 mg/L sodium sulfite was added per 1 mg/L for complete oxygen depletion.

Table 4: Experiments conducted with the two different tanks

Location	Wastewater Type	Conducted Experiments
Pilot-Scale (17,000 L)	Clean Water Tests (Effluent)	Time Settings Diffusers Energy Consumption
Pilot-Scale (17,000 L) Full-Scale (380,000 L)	Thickened Activated Sludge	Airflow Diffuser versus Diffuser/TotalMix System
Pilot-Scale (17,000 L)	Activated Sludge	Airflow Diffuser versus Diffuser/TotalMix System

Figure 15 shows the various combinations of airflow, diffusers and bulk liquid that were considered.

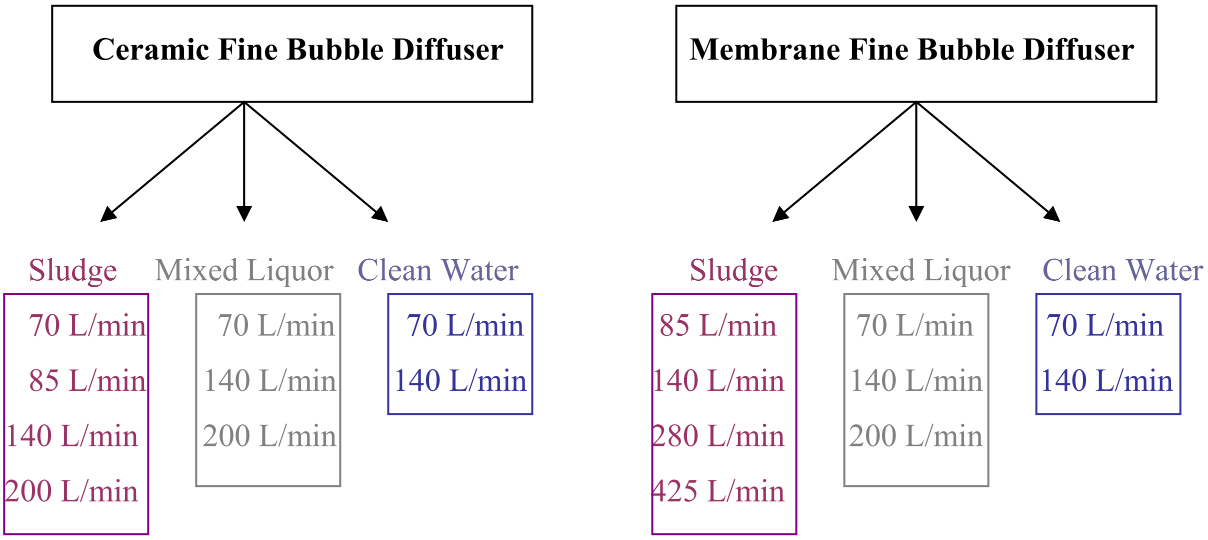


Figure 15: Overview of the experiments

The optimum set-up was determined carrying out clean water tests in the pilot-scale tank. DO concentrations were measured, with only the TotalMix as an aeration source, using different valve time settings (Table 5) and comparing the DO concentrations to each other. The time between air bursts (delay time) and the period of how long the air was released into the bulk liquid (air burst) were changed. Every trial was repeated 5 times on different days.

Table 5: Valve Time Setting

Delay [sec]	1	1	1	2	2	2
Air Burst [sec]	0.1	0.2	0.3	0.1	0.2	0.3

To identify the energy consumption of the new system, the current [amperes] used by the compressor and the ON- and OFF-time [sec] of the compressor were measured. Based on the fact that *ampere * time is proportional to the energy consumption*, energy can be calculated as area under the graph of time (y) vs. amperes (x). A power factor of 0.85 was used for all calculations.

$$E = \int U * t * dt \qquad (9)$$

Where,

E = Energy [kWh]
U = Voltage [W]
t = Time [h]

In comparing the standard aeration system with the new system, only the electrical current is important. Voltage can be neglected as it is the same for both systems and cancels itself out in a comparison of the systems. To integrate the different running times of the diverse aeration systems in the energy calculations, the summed up ampere-seconds of the systems are divided through the total running time of the standard aeration system. The result is the average amperes per time for each system and the energy ratio of the two systems can be reported.

4. Statistical Analysis

The data were analyzed using SAS statistical software. A type I error (α) of 0.05 was chosen for all statistics. The Shapiro – Wilks test was used to assess the distribution of the data sets. If the data were found to be not normally distributed, the two sample Wilcoxon test (nonparametric t test) was used to determine differences between two means. The F-test was performed to assess if data had equal variances. A Two-Way Analysis of Variance (ANOVA) was performed to test for differences between more than two means for two different factors. Levene’s test was used to determine homogeneity of variances. In case normality or homogeneity of variances was violated, the Friedman nonparametric Two-way ANOVA was used instead.

Results

The Results obtained from the experiments in both tanks indicated an enhancement in aeration efficiency and also more beneficial energy consumption when low airflow rates were used.

1. Aeration Efficiency

1.1. Pilot-Scale Tank (17,000 L)

1.1.1. Thickened Activated Sludge

The thickened activated sludge used in the pilot-scale tank had a total solids (TS) concentration of 4.9%. No dissolved oxygen concentration could be detected over a period of days. After diluting the sludge down to a concentration of TS = 1.2%, and after a stabilization time of 9 days, a small amount of dissolved oxygen was detected.

1.1.1.1.Total and Soluble Chemical Oxygen Demand (TCOD, SCOD)

TCOD and SCOD tests were performed to detect when the sludge was stabilized. Problems with the compressor, which turned off at night, three times (48h, 96h, and 120h), are the reasons for the inconsistency in the COD decrease (Fig. 16 and 17).

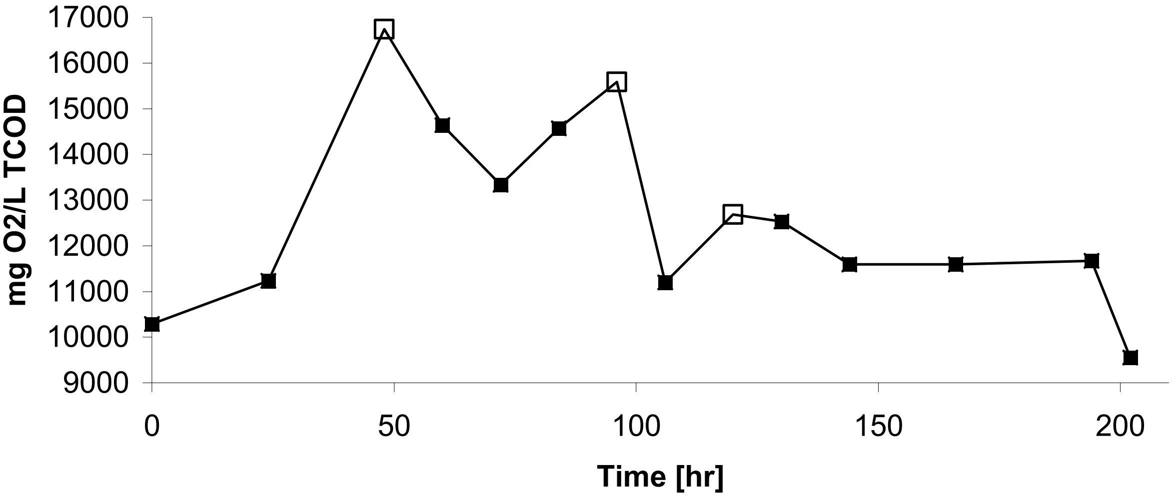


Figure 16: TCOD concentration over time during the stabilization of the thickened activated sludge (times when compressor was not working are represented by the open points)

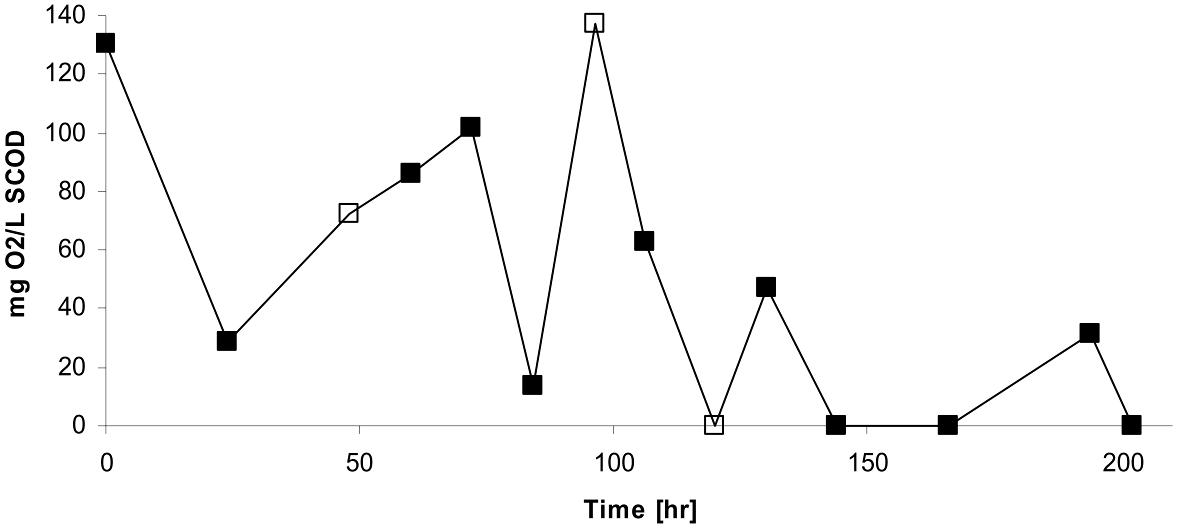
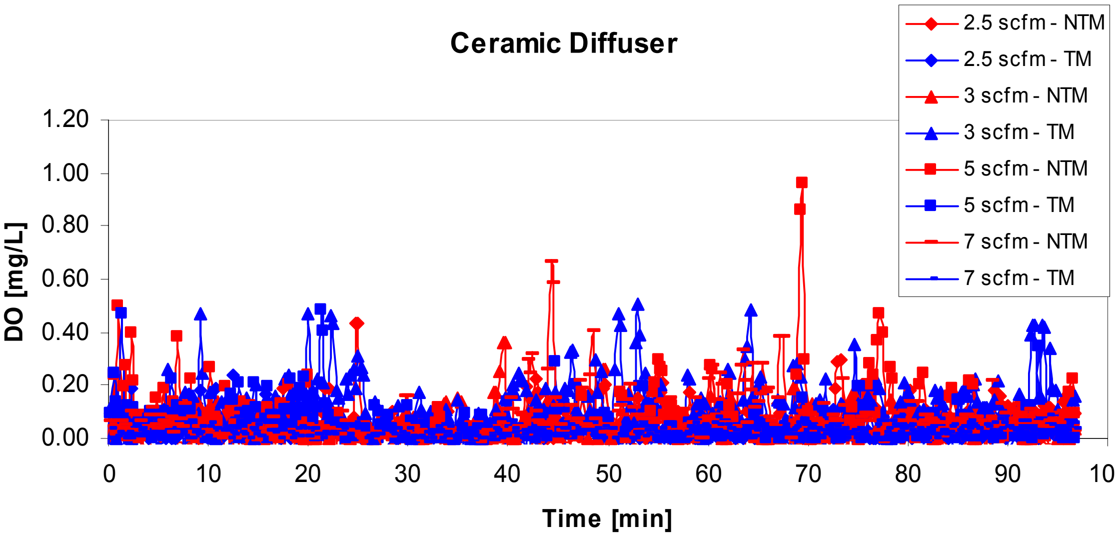


Figure 17: SCOD concentration over time during the stabilization of the activated thickened sludge (times when compressor was not working are represented by the open points)

The TCOD of 10,000 mg O_2/L and higher signify the high oxygen demand in the sludge and explain the impossibility of measuring DO during aeration in the thickened sludge. The relative low value at the beginning of the measurement is possibly the result from the filling and the inescapable aeration during this process.

1.1.1.2. DO in Activated Thickened Sludge

An overview of the dissolved oxygen concentrations in activated thickened sludge (TSS = 1.2%) indicates only minimal, if any, enhancement of OTR (Fig. 18) with the TotalMix system. This is due to the high TCOD levels of the sludge. Therefore, the level of other parameters, such as NO_3-N and NH_4-N, might indicate more convincingly that aeration was enhanced (Fig. 19 and 20).



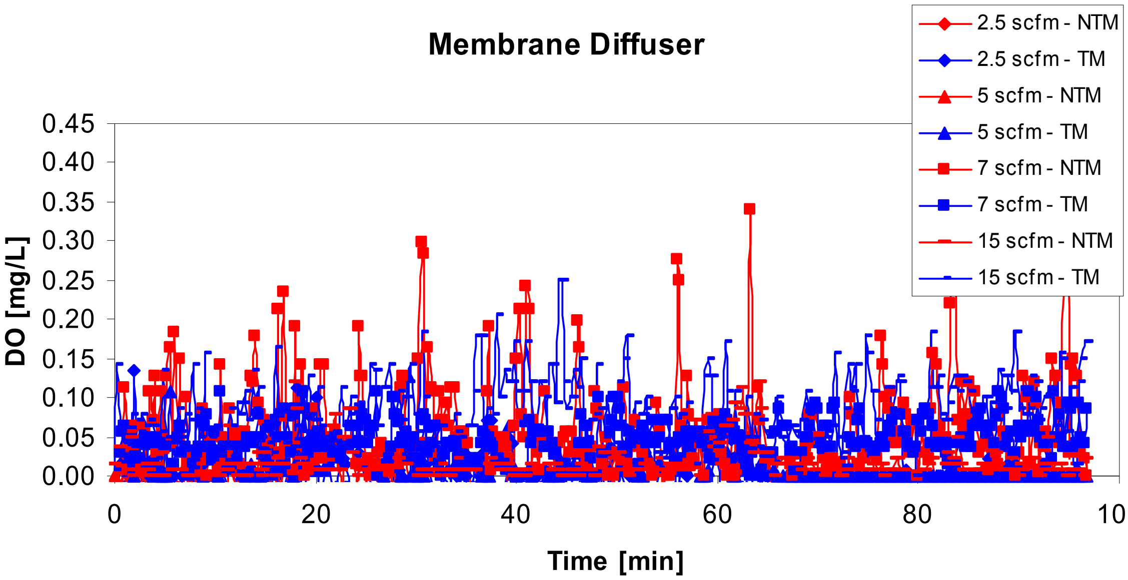


Figure 18: Overview of Dissolved Oxygen Concentration in Sludge over time, using different diffusers, airflow rates and different aeration systems (TM=TotalMix, NTM= no TotalMix)

The average DO concentrations for both diffusers were around 0.15 mg/L. Although the maximum concentration of 1.0 mg/L was measured with the ceramic diffuser, no significant distinction between ceramic diffusers and membrane diffusers was detected; neither were there statistically differences between standard aeration systems and the TotalMix/diffuser system. Exceptions were ceramic diffuser tests with an airflow rate of 85 L/min and the membrane diffuser experiment with an airflow rate of 425 L/min. Both tests showed a statistically significant improvement in the aeration efficiency when TotalMix was included (Table 6).

Due to the marginal amount of dissolved oxygen measured and considering the large value of the error bars in Figure 18 and 19, DO concentration does not seem to be a good parameter to measure in denser sludge. The DO data are more meaningful when combined with NO_3-N and NH_4-N data. Figures 19 and 20 display the DO concentrations of the different diffusers over time in comparison to the NO_3-N and NH_4-N data over the same time period.

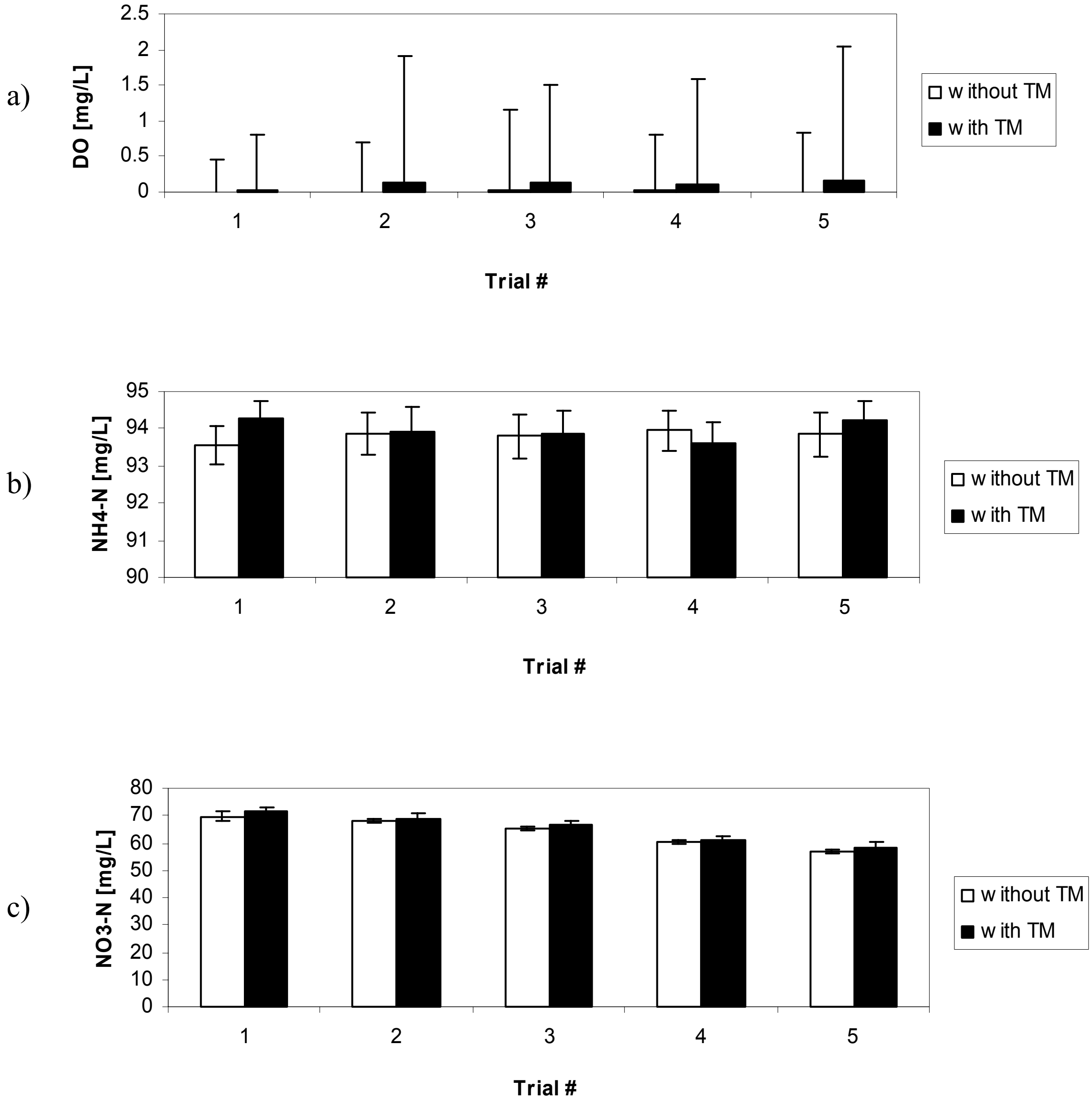


Figure 19: a) DO Concentration, b) NH_4-N and c) NO_3- Concentrations over time, measured while using a ceramic diffuser at an airflow rate of 85 L/min

The data suggests that the average dissolved oxygen concentration in the TotalMix/Standard Aeration system was about 1400% higher than using the standard aeration system alone. Yet, the large error bars in Figure 18a in combination with the NH_4-N (Fig. 198b) and NO_3-N (Fig. 19c) values do not support such an enhancement in aeration. With the NH_4-N data remaining relatively constant over the test period and the NO_3-N values decreasing, it appears that aeration was insufficient.

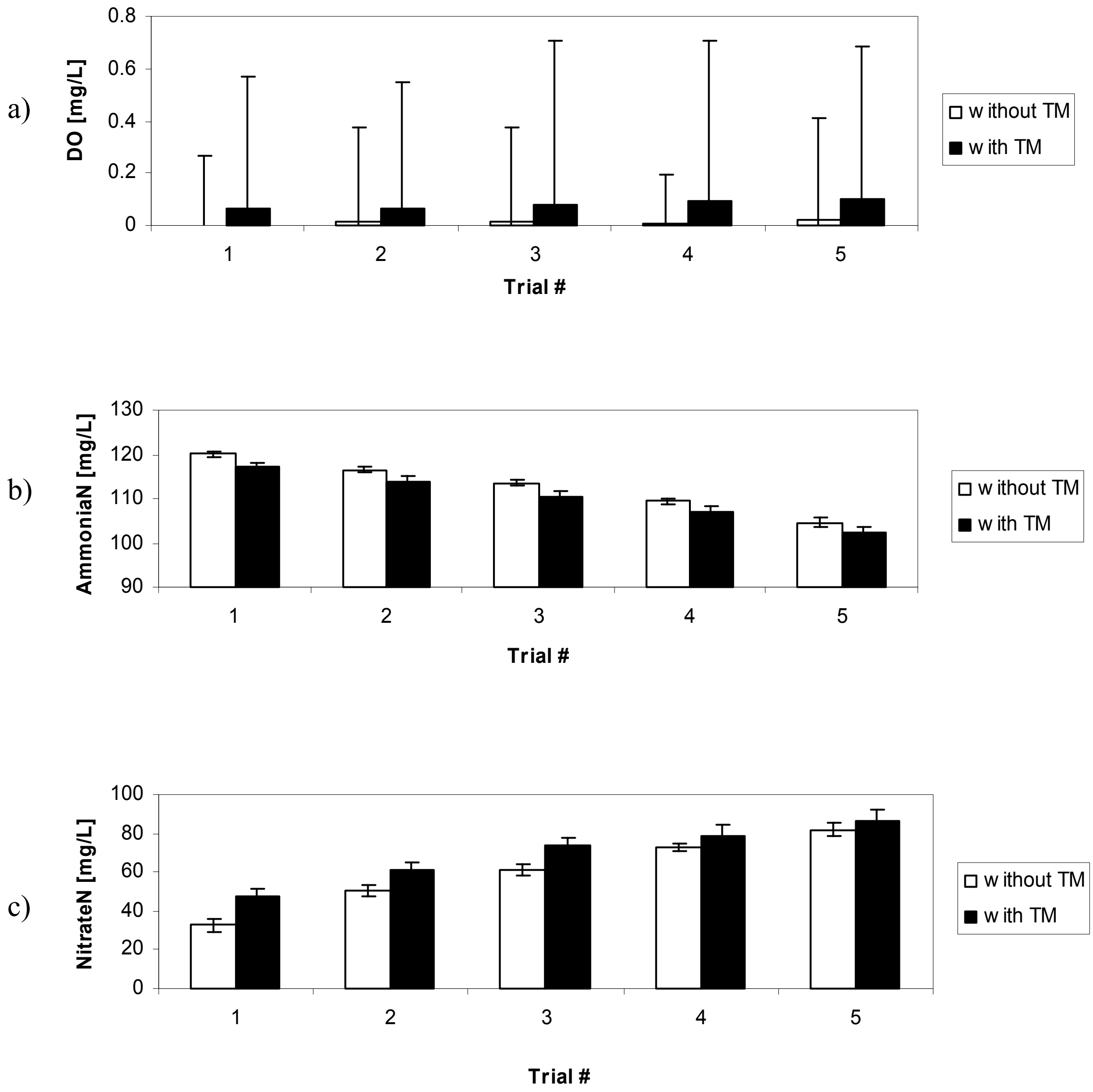


Figure 20: a) DO Concentration, b) NH_4-N and c) NO_3-N Concentration over time, measured while using a Membrane Diffuser at an airflow rate of 425 L/min

When the membrane diffuser was used with TotalMix, the maximum increase in DO concentration (Fig. 20a) was about 600%. Again, the error bars are high, but in contrast to the ceramic diffuser results, the NO_3-N (Fig. 20b) and NH_4-N (Fig. 20c) concentrations indicate that aeration was sufficient. Ammonium values decreased over time, while nitrate concentrations increased, and TotalMix seemed to enhance biological activity. The nitrification occurred 1.4 times faster with the TotalMix system in use. The mean values for all experiments can be seen in tables in the Appendix (Table A1 – A8).

1.1.2. Activated Sludge

This sludge, derived from the outlet of the aeration basin, had a lower chemical oxygen demand and therefore made it possible to measure higher concentrations of dissolved oxygen.

1.1.2.1. DO Concentration in Activated Sludge

Data collected from activated sludge studies showed that TotalMix improved the aeration rate. The overviews (Fig. 21 and 22) of the DO concentrations in mixed liquor (TSS = 1.2%) showed an increase in aeration efficiency at all airflow rates and with both diffuser types.

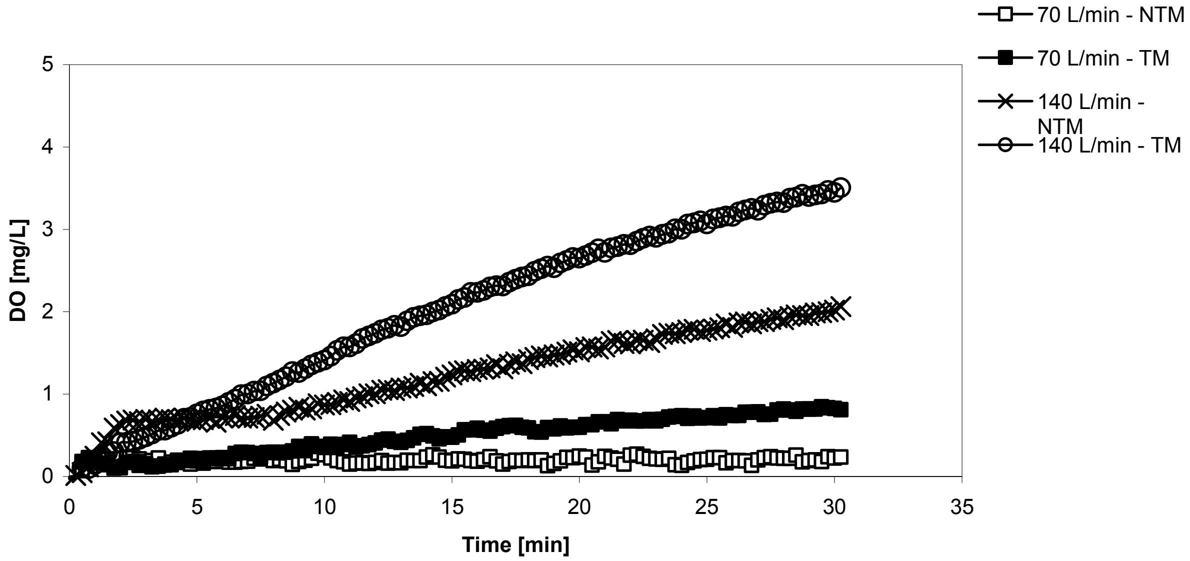


Figure 21: Overview of DO concentration in activated sludge over time, using ceramic diffuser, airflow rates and different aeration systems (TM=TotalMix; NTM=no TotalMix)

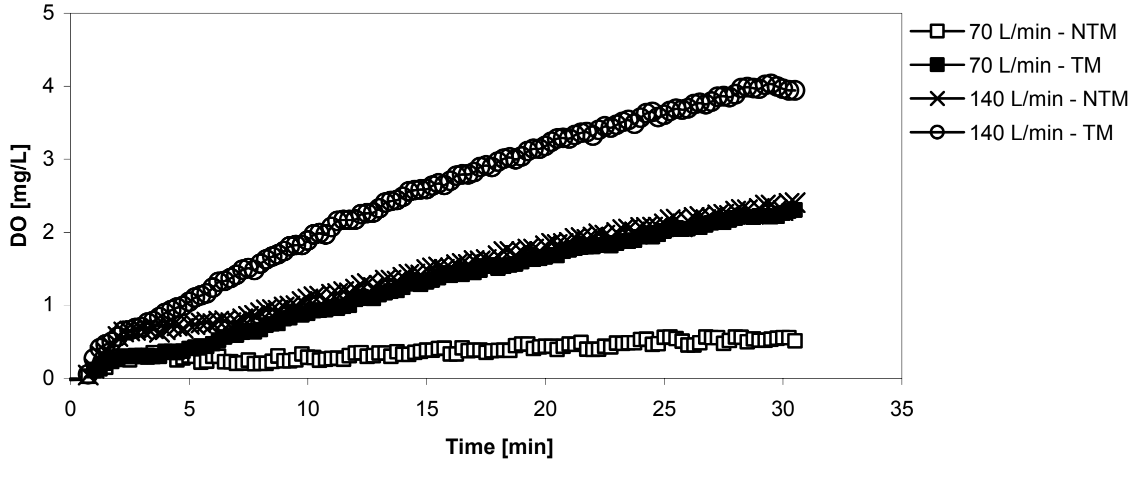


Figure 22: Overview of DO concentration in activated sludge over time, using membrane diffuser, airflow rates and different aeration systems (TM=TotalMix; NTM=no TotalMix)

It can be seen from Figures 21 and 22 that TotalMix was in every test superior to the standard aeration system. TotalMix in combination with the ceramic diffuser achieved the highest DO concentration (3.5 mg/L) at an airflow rate of 200 L/min, however, at 140 L/min only slightly less DO (3.3 mg/L) was measured. The same is true for the membrane diffuser when combined with TotalMix, the highest DO concentration (4.0 mg/L) was found at an airflow rate of 200 L/min. Figure 22 shows in greater detail the differences between the TotalMix/diffuser system and standard diffusers.

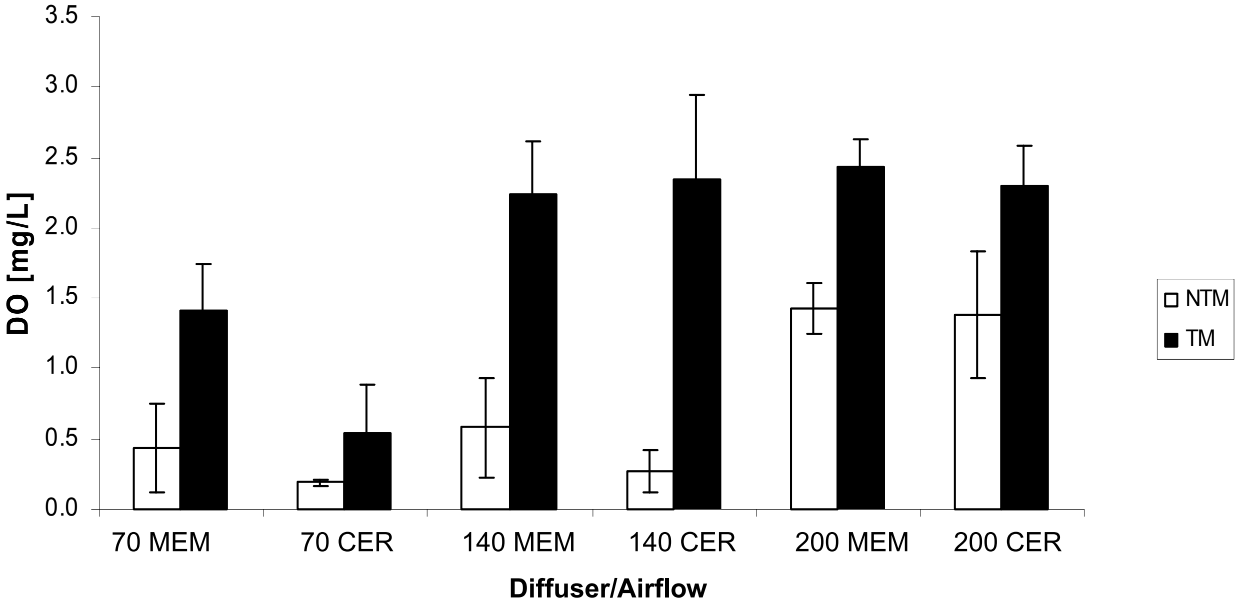


Figure 23: Comparison of Dissolved Oxygen Concentrations in Activated Sludge for different Diffusers, Airflow rates and Aeration Systems (MEM = membrane diffuser, CER = ceramic diffuser, 70, 140, and 200 are the airflow rates in L/min, NTM=no TotalMix, TM=TotalMix)

The results of the aeration tests with activated sludge using a ceramic diffuser showed the highest absolute value at an airflow rate of 200 L/min, yet, the improvement in aeration with the TotalMix system at this airflow rate was the lowest of all tests (67%). The highest increase (ca. 700%) in DO concentration was measured at an airflow rate of 140 L/min (Fig. 23). This result is not surprising as fine bubble diffusers tend to be less efficient when operated at higher airflows. Manufacturers often recommend an airflow rate of 40 to 80 L/min due to the higher headloss at higher flow rates.

1.2. Summary of Tests in Pilot-Scale Tank (17,000 L)

The majority of the results obtained from the tests with the pilot-scale tank supported our hypothesis that including TotalMix in aeration units will increase the dissolved oxygen concentration and, therewith, increase the oxygen transfer rate.

Testing in thickened activated sludge proved to be more difficult due to its high chemical oxygen demand. Dissolved oxygen introduced through the aeration system was consumed immediately and therefore was not the best parameter for the evaluation of the system. Some of the seemingly contradictory results given in Table 6 are due to the fact that the data were averaged, but the values also reflect the difficulties in measuring dissolved oxygen in thickened activated sludge. The trends of other parameters such as NO_3-N, NH_4-N, and COD seem were useful in evaluating aeration efficiency when oxygen demand is high.

A summary of all the experiments conducted in the experimental tank is given in Table 6. The data are averaged from all the various trials. The mean values of all experiments can be found in the Appendix (Table A9 – A14).

Table 6: Summary of p-values and Increase in DO Concentrations for the Experiments Conducted in the Pilot-Scale Tank (α = 0.05)

Wastewater	Diffuser	Airflow [L/min]	Increase of DO [%]	p-value	Significant difference between standard aeration system vs. TotalMix
Thickened activated sludge	ceramic	70	0	2.95E-07	Yes
		85	739	< 2.2 e-16	Yes
		140	0	3.19E-01	No
		200	0	1.63E-01	No
	membrane	85	0	1.9E-13	Yes
		140	0	2.3E-08	Yes
		280	0	3.1E-01	No
		425	532	< 2.2 e-16	Yes
Mixed Liquor	ceramic	70	223	< 2.2 e-16	Yes
		140	186	8.9E-14	Yes
		200	286	2.7E-13	Yes
	membrane	70	782	< 2.2 e-16	Yes
		140	71	1.3E-06	Yes
		200	67	7.5E-10	Yes

1.3. Full-Scale Tank

The tests were performed under actual conditions using the pressure and airflow normally used at the turf farm.

1.3.1. Activated Sludge

1.3.1.1 Valve Time evaluation

The opening intervals of the valves controlling the TotalMix heads were changed and in every trial the DO concentration was measured at the third beam (in the middle of the tank, no aeration devices below). Those obtained DO values were compared to each other to detect the most efficient valve time setting (Fig. 24). As a control, the dissolved oxygen was measured without using the TotalMix system but only aerating with only the coarse bubble diffusers instead.

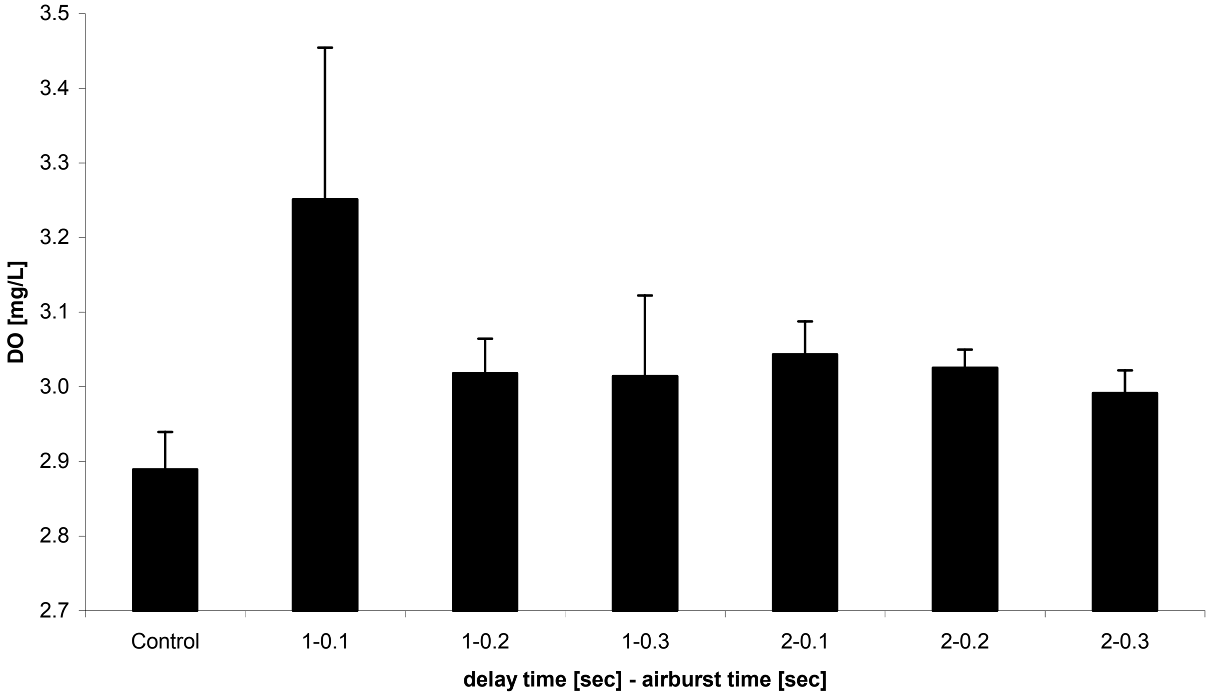
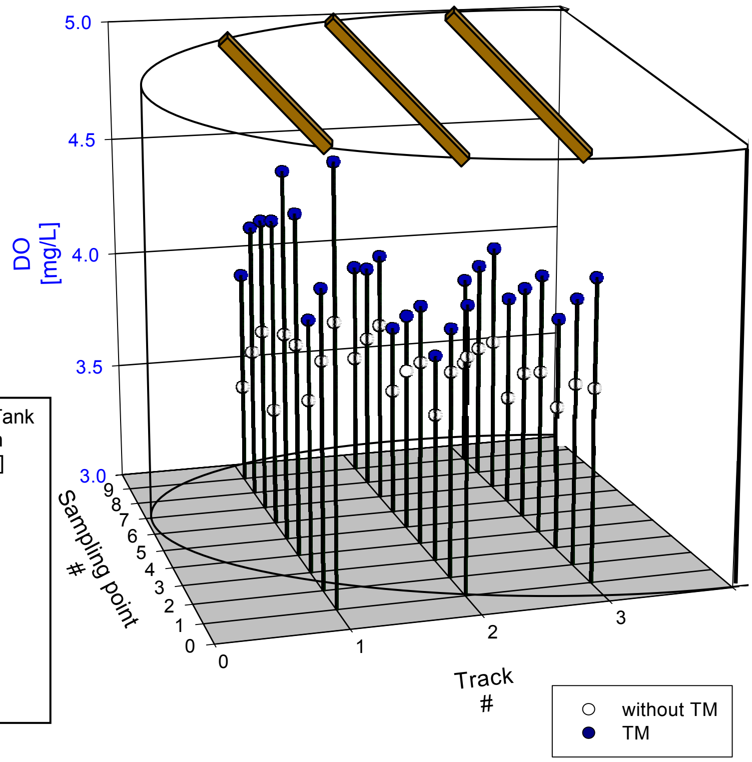


Figure 24: Comparison of the DO-concentration relating to the different valve time settings

The control with 2.9 mg/L provided the lowest measured DO concentrations. An airburst of 0.1 seconds and a 1 second delay time increased the DO concentration by 12.5% to 3.3 mg/L. Other trials provided more or less the same DO concentrations of about 3 mg/L and an improvement of in average 4%.

1.3.1.2. DO Concentration

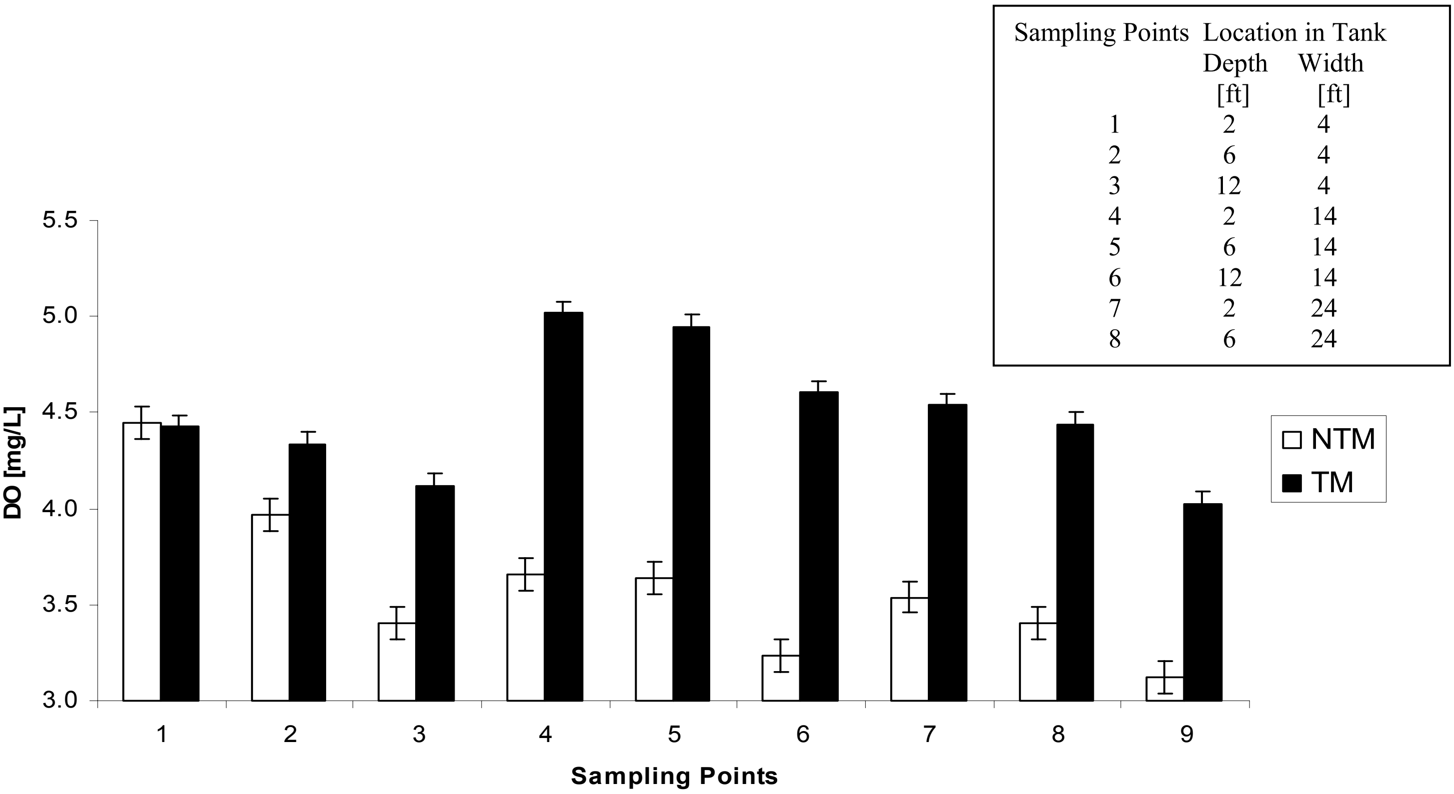
The results showed that at all the 27 sampling points the DO concentration were increased due to the application of the TotalMix System. Figure 25 shows the dissolved oxygen concentrations at each sample point with and without TotalMix.



Sampling Points #	Location in Tank Depth [ft]	Location in Tank Width [ft]
1	2	4
2	6	4
3	12	4
4	2	14
5	6	14
6	12	14
7	2	24
8	6	24
9	12	24

Figure 25: Simplified Schematic of an Overview of the DO-concentrations in one half, in the full scale tank containing thickened activated sludge (TSS = 1.3%) (TM= TotalMix) at the respective sampling tracks and depths

Although the TotalMix system improved the DO concentration on all sampling points, there were differences in efficiency. The highest absolute DO concentration for this experiment of 4.7 mg/L was measured at the first track at a depth of 0.6 m and in 1.2 m distance. This first track was located over the TotalMix system and also showed the highest average increase of DO concentrations (14%) compared to the other beams. The lowest values of about 3.4 mg/L and lowest average increase in DO concentrations (7%) were measured on the second track, which was placed above the standard diffuser system. Interestingly, data obtained from the third beam, located in the middle of the tank, still indicated a relatively high improvement of in average 11% and DO concentrations of 4 mg/L. These results indicate that the TotalMix system decreases dead spots and improves the overall mixing and aeration performance in the wastewater



Sampling Points	Location in Tank Depth [ft]	Width [ft]
1	2	4
2	6	4
3	12	4
4	2	14
5	6	14
6	12	14
7	2	24
8	6	24

Figure 26: DO-concentrations from the third track in the 100,000 gallon tank at different depths and distances (NTM= no TotalMix, TM= TotalMix)

All the data reported from the full scale tank on all three beams with the TotalMix system were significantly different from the data obtained in the full scale tank with standard aeration only ($p < 0.0001$, R2 = 0.80, $\alpha = 0.05$) and revealed that DO levels where greater when TotalMix was used. The data shown in Figure 26 was collected from the third beam which was located in the center of the tank. No aerators were directly below it.

2. Energy Conservation

2.1. DO Concentration

Clean water tests were performed in the pilot scale tank and showed that every set-up was enhanced by the TotalMix system. In Figure 27 all the data are plotted, so that DO levels under different conditions can be easily compared. The trials with TotalMix system are plotted in fine lines, without the TotalMix system are diagrammed in black open squares. The results from all experiments showed, that the TotalMix system is more efficient under all test conditions than using the standard diffuser alone.

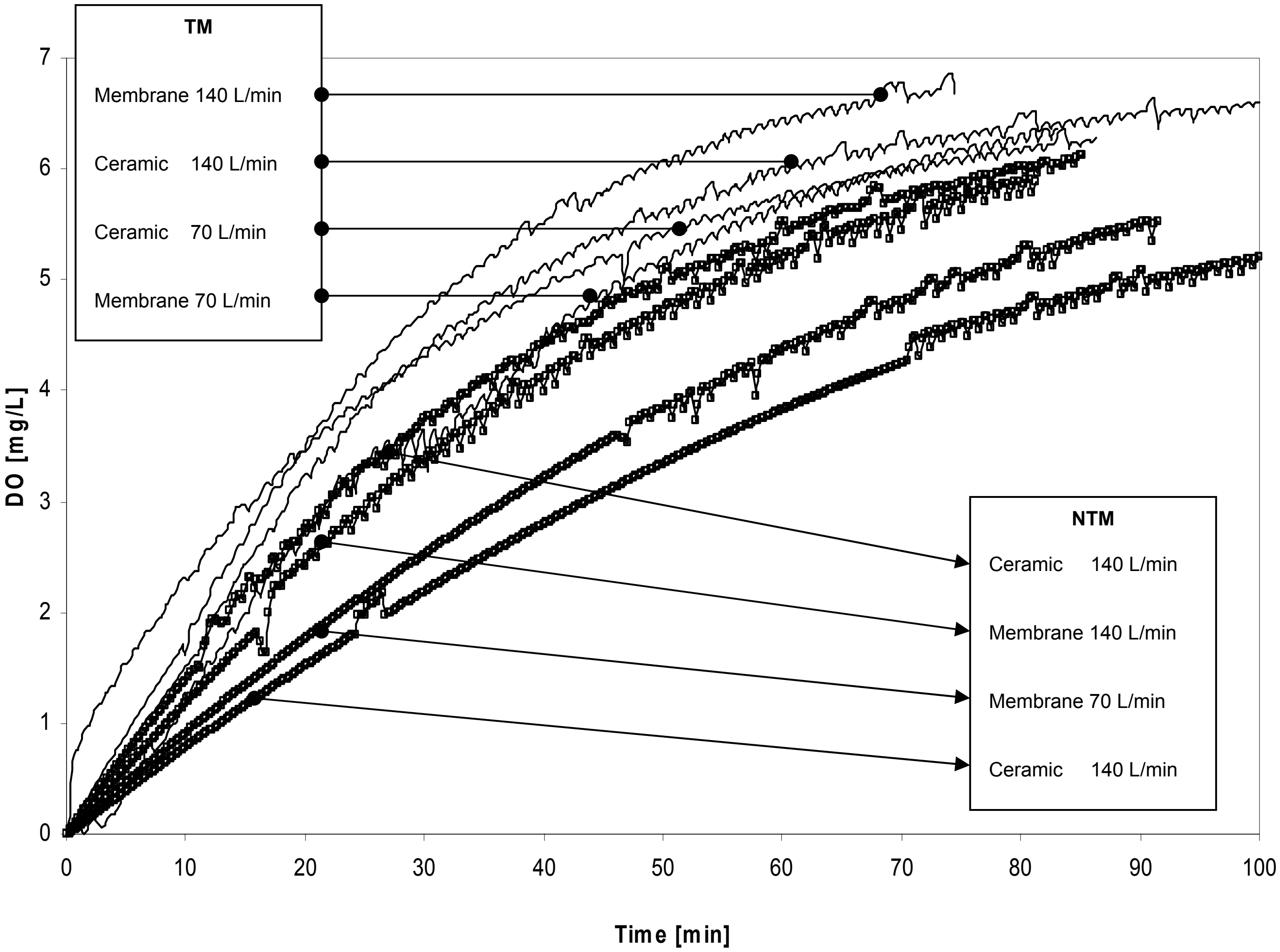


Figure 27: Overview of Diffuser, Airflow rates and Aeration System obtained from Clean Water Tests at different airflow rates and with different diffusers (NTM = no TotalMix, TM = TotalMix)

The most efficient airflow rate was seen with the membrane diffuser and the TotalMix system at an airflow rate of 140 L/min (Fig. 27). The largest improvement in aeration efficiency was achieved with a ceramic diffuser and the TotalMix system at an airflow rate of 70 L/min (Fig. 28). This aeration combination reached 50% (ca. 3.5 mg/L) oxygen saturation in the clean water after about 22 minutes, whereas the ceramic diffuser alone needed about 55 minutes to reach 50% of the oxygen saturation.

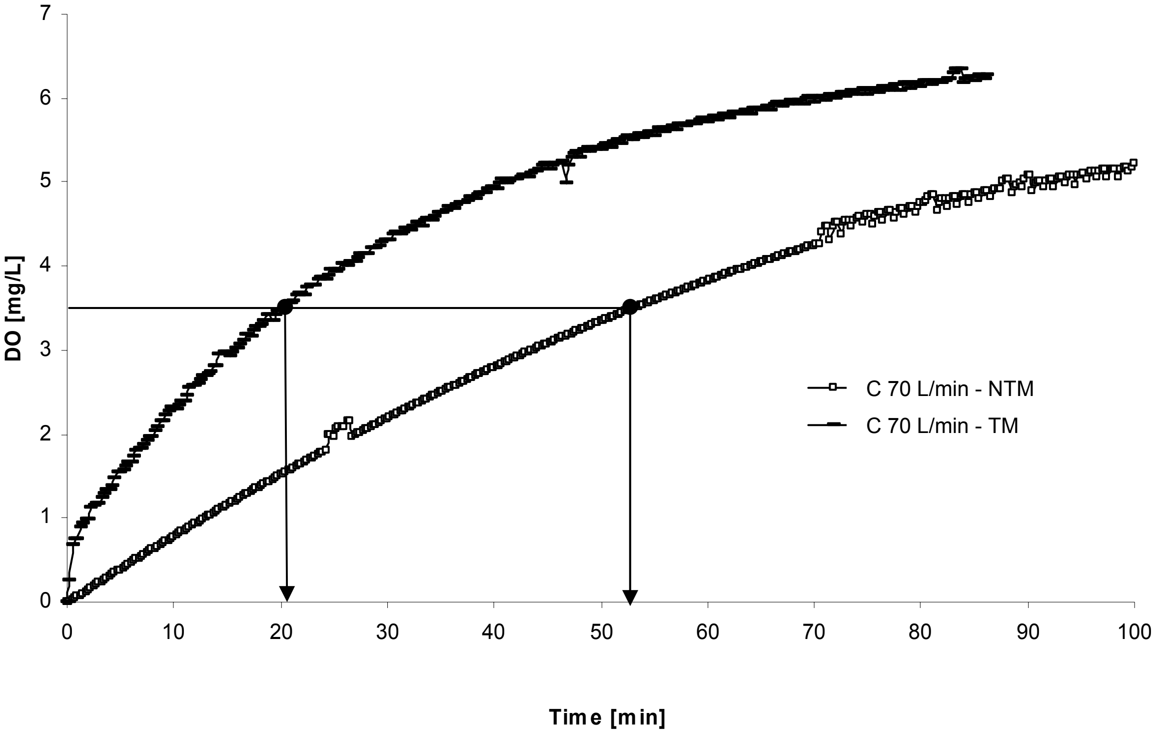


Figure 28: Improvement in aeration efficiency at an airflow rate of 70 L/min using a ceramic diffuser (open squares) versus TotalMix system (black lines)

The ASCE DO Parameter Estimation Program (DO_PAR 1.08; ASCE 1997; downloaded from: http://fields.seas.ucla. Edu/research/dopar/) was used to calculate K_La [1/hr], SOTE under clean water conditions [%], and SOTR [kg/hr] under standard conditions. The K_La and the SOTR in the following are used to describe the mass transfer and the efficiency of the respective systems. The calculated K_La and SOTR values for ceramic and membrane diffusers are summarized in Tables 7 and 8 and are consistent with data found in the literature (Mahendraker et al. 2005) with K_La values between 0.12-1.8 hr^{-1}. Higher K_La of up to 13.4 hr^{-1} can be achieved with more fine bubble diffusers in use (Gillot et al. 2005). SOTR and SOTE data could not be compared with data literature due to different flow rates or numbers of diffusers used.

Table 7: Summary of K_La, Standard Oxygen Transfer Efficiency (SOTE), and Standard Oxygen Transfer Rate (SOTR) Calculations for Ceramic Diffuser at Standard Conditions (20°C) and different airflow rates (NTM = no TotalMix, TM = TotalMix)

Airflow rate	K_La [1/hr]	SOTE [%]	SOTR [kg/hr]	Increase with TM-system %
70 L/min NTM	0.450	98.5	1.16	150
70 L/min TM	1.543	246.6	2.90	
140 L/min NTM	1.276	210.7	2.48	30
140 L/min TM	1.640	137.5	3.23	

Table 8: Summary of K_La, Standard Oxygen Transfer Efficiency (SOTE), and Standard Oxygen Transfer Rate (SOTR) Calculations for Membrane Diffuser at Standard Conditions (20°C) and different flow rates (NTM = no TotalMix, TM = TotalMix)

Airflow rate	K_La [1/hr]	SOTE [%]	SOTR [kg/hr]	Increase with TM-system %
70 L/min NTM	0.550	117.3	1.38	83
70L/min TM	1.196	214.8	2.52	
140 L/min NTM	1.050	91.5	2.15	63
140 L/min TM	1.665	149.3	3.51	

At every airflow rate and with every type of diffuser more oxygen per time was delivered with the TotalMix system in use. The lowest increase with 30% higher SOTR was achieved with a ceramic diffuser and the TotalMix at an airflow rate of 40 L/min. The same combination at a lower airflow rate of 70 L/min produced an increase in SOTR of 150%.

2.2. Energy Consumption

The compressor supplying the air for the aeration systems was ON longer when the TotalMix system was used. The differences in ON - and OFF - time varied depending on the diffusers and airflow rates used (20 to 60 min). The longer running time (larger area under the graphs) of the compressor with the TotalMix system, was compensated by the higher aeration efficiency, which allowed for a decrease in compressor operation time (Fig. 29).

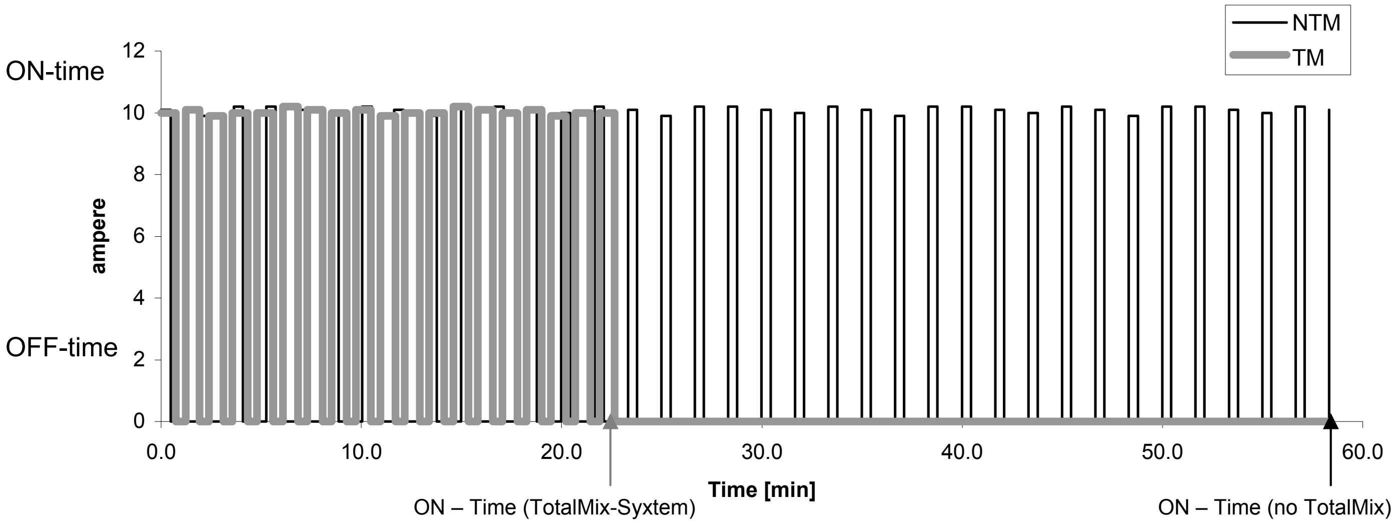


Figure 29: Comparison of Ampere Consumption over time using a Ceramic Diffuser at 70 L/min

The area under the graphs in Figure 29 is proportional to the energy consumed. Based on the fact that E = ∫U* t *dt, energy can be calculated for every aeration system. For comparison of the two aeration systems, the voltage, which is the same for both systems, can be disregarded, and only the electrical current (amps) is important for the calculation. The energy consumed is proportional to the amps used multiplied by the ON-time. The result of this multiplication for each aeration system is then divided by the total ON- and OFF-time of each respective aeration system and the result is the average ampere used. The data for all experiments can be found in the Appendix (Table A15 – A19).

The voltage played a role when the energy consumed was calculated. Then, the voltage was multiplied by the average amperes and the total time (ON and OFF). The results of this calculation can be seen in Figure 30.

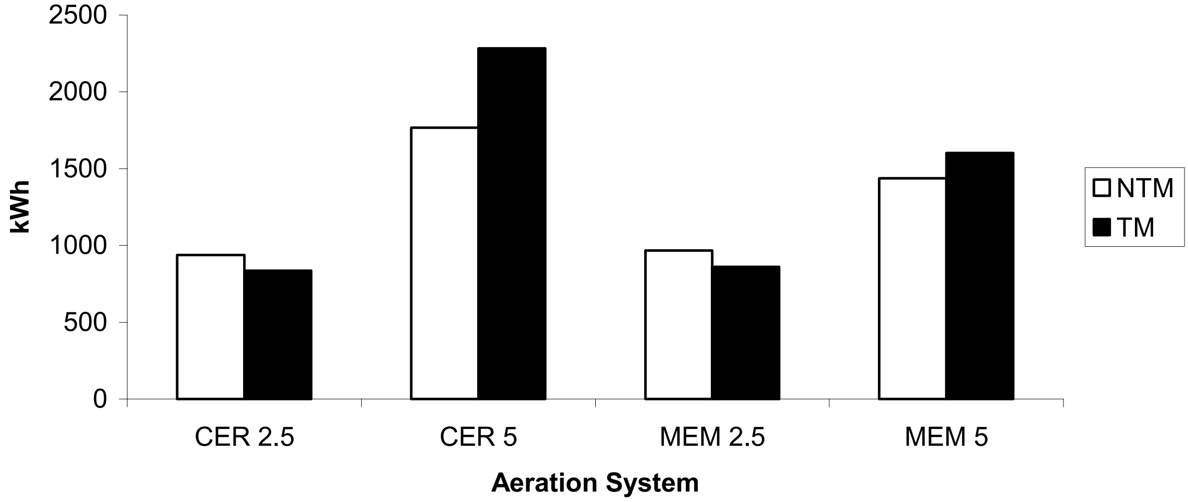


Figure 30: Comparison of average Energy [kWh] values for the different aeration systems (NTM= no TotalMix, TM= TotalMix) at different airflow rates (2.5 and 5 scfm = 70 L/min and 140 L/min)

The energy consumed (Fig. 30) varied widely depending on the diffusers used and adjusted airflow rate. The data indicate the lower airflow rates (70 L/min) favor use of the TotalMix system in terms of energy consumption, whereas the higher airflow rates (140 L/min) favor standard aeration systems. At the lower airflow rates the standard aeration system consumed up to 1.12 times more energy than the system with TotalMix. All energy ratios are provided in Table 9.

Table 9: Overview of the Energy Consumption Ratio of the different Set-Ups

Diffuser type and Airflow [L/min]	NTM : TM
Ceramic, 70	1.12 : 1
Ceramic, 140	1 : 1.29
Membrane, 70	1.12 : 1
Membrane, 140	1 : 1.11

2.3. Aeration Efficiency

To characterize the efficiency of the different aeration systems, the ratio between the SOTR and the power consumed was calculated. A comparison between the different aeration systems shows that the TotalMix system provides higher aeration efficiency than standard fine bubble diffusers for all airflow rates (Table 10).

Table 10: Comparison of Aeration Efficiency between TotalMix system and different fine bubble diffusers at different airflow rates (NTM = no TotalMix, TM = TotalMix)

Diffuser	Airflow [L/min]	**NTM** Aeration Efficiency [kgO_2/kWh]	**TM** Aeration Efficiency [kgO_2/kWh]
Ceramic	70	0.32	0.71
Ceramic	140	0.39	0.72
Membrane	70	0.83	0.90
Membrane	140	0.61	0.98

The aeration efficiency for membrane diffusers is enhanced by 8% at an airflow rate of 70 L/min and almost by 60% at an airflow rate of 140 L/min. For ceramic diffusers the difference is even more pronounced with an increase in aeration efficiency of about 80% at an airflow rate of 140 L/min and 120% at a lower airflow rate of 70 L/min.

Discussion

The simplest way to increase oxygen levels would be to increase the airflow rate of aeration systems. A doubling of the airflow rate results in a 90% increase in OTR (Ashley et al. 1991). The problem with this approach is that an increase in airflow rate also increases the energy consumption and costs of a treatment facility. The TotalMix system avoids this dilemma. Although an additional aeration source is needed with TotalMix the main focus is on enhancing mixing and reduction of the energy consumption.

Results of field experiments performed using activated sludge in a pilot scale tank, as well as in the full scale tank, showed significant increases in DO concentrations in activated sludge when the new pneumatic mixing system, TotalMix, was used. In the full scale tank the increase in DO concentration ranged from about 15% to 270% across all sampling points. The pilot scale tank showed a greater range, due to the different diffusers used and different airflow rates applied. The increase in DO concentrations was between 67% and 700% for the results obtained in the pilot scale tank. Additionally, ceramic diffusers are reputed to have fewer problems with clogging than membrane diffusers and are also more efficient over time than membrane diffusers (Libra et al. 2005).

These significant improvements in DO concentration are due to the addition of the TotalMix into the standard aeration system. Indeed TotalMix adds more oxygen into the bulk liquid but more importantly it improves the aeration efficiency of the standard diffuser. An increase in DO concentration of 700% can not be achieved by simply increasing the airflow rate. Aside from the enormous increase in energy consumption, higher airflow rate leads to a reduced bubble retention time and to less efficient oxygen transfer (Gillot 2000). The TotalMix system, however, improved the DO concentration by concomitantly decreasing the energy consumption at low airflow rates (70 L/min). According to Stenstrom (1996) the greatest transfer efficiencies can be achieved with aeration systems that spread air across the basin floor as much as possible. The TotalMix meets this requirement by introducing high pressure bursts of air in a horizontal direction for as much as 46 cm from the TotalMix head into the wastewater. Its mode of operation could be the key factor for the increase in retention time of the fine bubbles provided by the diffusers and therefore, the improvement of the oxygen transfer rate and ultimately the increase in aeration efficiency.

Aeration efficiency calculations showed that including the TotalMix system increased the aeration efficiency between 8% and 120%, dependant on the type of diffuser used. These results also indicate that doubling the airflow rate does not lead to a significant improvement in aeration efficiency. This might be due to the higher headloss at higher airflow rates (Gillot 2000; Roustan 1996).

Furthermore, the TotalMix system indicated better mixing capabilities. The DO concentration in the full scale tank was more homogeneously dispersed than the DO dispersion with the standard diffuser.

Tests in the thickened activated sludge also indicated, that aeration was improved by TotalMix. Unlike the experiments in the activated sludge, the main parameter used to evaluate the efficiency of the TotalMix system in the thickened wastewater, was the nitrogen removal efficiency by nitrifiers. Digesters usually have low nitrification rates, which can be increased, when the system is operated towards optimum conditions (Genc et al. 2002). Autotrophic nitrifiers play an essential role in aerobic treatment of domestic wastewater. The two main genera, responsible for the oxidation of ammonium to nitrite and further transformation of nitrite to nitrate, are Nitrosomonas and Nitrobacter respectively (Muller et al. 1995). Nitrification is inhibited in systems with high COD levels, where autotrophic nitrifiers can usually not successfully compete with heterotrophic bacteria (Genc et al. 2002). This will lead to low nitrification due to the overwhelming activity of the heterotrophs (Campos et al. 2007). Furthermore, if oxygen is the limiting factor, then an incomplete oxidization of ammonium can occur, leading to an accumulation of nitrite and its presumed toxic effects on the biomass in the wastewater (Muller et al. 1995). Results from the experiments with the TotalMix system indicated that nitrification occurred 1.4 times faster than in standard aeration systems. The TotalMix system can supply air more efficiently and more homogeneously and, it seems, that enough oxygen can be provided to achieve a sufficient nitrogen removal, even in wastewaters with a high carbon to nitrogen ratio (C/N). This approach should be investigated more closely.

Usually, industrial operations produce wastewaters with a low C/N ratio, reducing the influence of heterotrophs on nitrification (Wiesmann 1994) and leaving sufficient DO for the nitrifiers. The better aeration enabled by the TotalMix system seemed to provide a better environment for nitrifiers. Nitrite-oxidizing bacteria should benefit more than ammonia oxidizers from the new system due to their higher oxygen affinity constant (1.1 mg O_2/L)

(Wiesmann 1994). An accumulation of nitrite would be avoided and the required nitrogen removal could be achieved faster, decreasing the retention time of the bulk liquid in the tank.

Another approach for wastewaters with low C/N ratio, is to perform a shortcut by partially oxidizing ammonium to nitrite with a subsequent reduction of nitrite to nitrogen gas (Pollice et al. 2002). This described shortcut has, among other advantages, a lower oxygen demand, resulting in up to 25% energy savings (Beccari et al. 1983). The disadvantages of this shortcuts are the accumulation of nitrite and its presumed toxic effects on the biomass (Muller et al. 1995) and that the oxygen supply needs to be controlled and constantly observed in order to sustain ammonium oxidizers (Pollice et al. 2002). According to Pollice et al. (2002), this mode of operation depends on two main factors, the oxygen supply and the sludge age. Their results showed, that the sludge age is the critical parameter for partial nitrification when the oxygen supply is not limiting. Under limiting conditions (alternating oxygen supply) they observed complete transformation to nitrite. The TotalMix system makes it easier to control the oxygen supply and therefore can react quicker to changing conditions in the tank and, ideal conditions for the ammonium oxidizers as well as for the reduction of nitrite to nitrogen gas can be maintained.

Conclusion

A new pneumatic mixing device, TotalMix, was evaluated in pilot and full scale wastewater tanks. The combinations of TotalMix with standard aeration diffusers lead to a higher aeration efficiency and more homogeneous DO distribution. The combination of ceramic fine bubble diffusers with the TotalMix at low airflow rates of 70 L/min increased the aeration efficiency up to 120% and concomitantly reduced the energy consumption by 10%. The self-cleaning TotalMix system requires less maintenance and can be retrofitted into every type of aeration unit. To assess all possible applications of the TotalMix system more research should be conducted. The focus of future studies should be on nitrification in activated sludges with a high C/N ratio and on systems that use the shortcut approach.

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Appendix

Table A 1: Thickened Activated Sludge, Ceramic Diffuser, 70 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	0.009	0.37	116.14	98.68	6.57	9.24
2	-0.31	0.68	104.56	101.38	9.04	11.26
3	0.15	0.04	96.84	98.3	13	13.47
4	0.64	0.1	97.64	96.66	17.16	22.68
5	1.24	0.305	96.68	96.31	27.28	31.31

Table A 2: Thickened Activated Sludge, Ceramic Diffuser, 85 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	-0.36	0.54	93.55	94.26	69.68	71.3
2	0.07	1.84	93.86	93.94	68.22	68.7
3	0.4	1.73	93.8	93.85	65.32	66.55
4	0.31	1.68	93.95	93.63	60.28	60.83
5	0.1	2.28	93.85	94.25	56.89	58.28

Table A 3: Thickened Activated Sludge, Ceramic Diffuser, 140 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	1.52	2.04	94.49	93.86	56.26	57.71
2	1.07	1	93.51	93.27	57.38	58.89
3	0.47	0.4	98	98.71	14.54	25.04
4	0.79	0.43	99.07	99.3	23.58	31.54
5	0.45	0.19	99.43	99.17	27.53	34.96

Table A 4: Thickened Activated Sludge, Ceramic Diffuser, 200 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	0.77	0.17	94.71	89.61	33.27	38.28
2	0.25	0.25	87.6	86.41	40	45.93
3	0.26	0.26	86.25	85.76	49.05	50.45
4	1.46	0.3	85.83	84.69	45.38	50.15
5	0.9	0.44	84.53	83.67	52.6	58.075

Table A 5: Thickened Activated Sludge, Membrane Diffuser, 85 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	-0.23	-0.06	116.07	118.3	7.43	11.18
2	-0.39	-0.17	120.71	120	10.7	16.43
3	-0.41	-0.15	120.7	120.74	14.81	18.38
4	-0.46	-0.24	120.81	121.4	16.83	21.3
5	-0.41	-0.27	121.47	120.83	19.57	24.5

Table A 6: Thickened Activated Sludge, Membrane Diffuser, 140 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	-0.42	-0.08	83.14	82.54	43.00	50.65
2	-0.35	-0.01	82.98	82.36	51.89	58.28
3	-0.31	-0.03	83.05	82.71	55.20	59.87
4	-0.25	-0.05	83.21	82.98	57.49	62.34

Table A 7: Thickened Activated Sludge, Membrane Diffuser, 280 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	0.65	0.37	83.41	82.92	61.63	67.18
2	0.75	0.46	83.88	83.52	65.21	71.27
3	0.78	0.60	84.62	83.84	69.42	75.88
4	0.65	0.60	85.95	85.04	53.63	67.78
5	0.81	0.71	86.97	85.43	66.16	72.76

Table A 8: Thickened Activated Sludge, Membrane Diffuser, 425 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	-0.06	0.95	120.11	117.03	32.7	47.18
2	0.25	0.96	116.42	114	50.45	61.24
3	0.21	1.15	113.49	110.35	61.11	73.38
4	0.09	1.35	109.39	107.23	72.5	78.83
5	0.29	1.38	104.68	102.51	81.83	86.7

Table A 9: Activated Sludge, Ceramic Diffuser 70 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	3.01	1.55	68.20	65.69	26.37	28.01
2	2.70	7.71	64.40	63.57	29.34	30.79
3	2.28	13.58	62.87	62.60	31.12	32.89

Table A 10: Activated Sludge, Ceramic Diffuser, 140 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	2.05	25.61	62.46	61.87	28.70	31.75
2	6.74	28.89	61.68	61.88	30.68	32.65
3	2.48	44.83	63.55	63.35	20.49	26.09

Table A 11: Activated Sludge, Ceramic Diffuser, 200 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	14.84	27.20	65.25	65.75	25.28	24.98
2	14.99	33.13	67.18	67.76	24.36	26.08
3	28.39	36.83	67.90	68.72	26.64	27.72

Table A 12: Activated Sludge, Membrane Diffuser, 70 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	3.95	15.89	69.08	69.12	26.34	27.68
2	2.15	17.45	68.75	69.24	26.77	27.57
3	12.44	26.51	68.94	68.87	28.68	30.30

Table A 13: Activated Sludge, Membrane Diffuser, 140 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	2.78	39.08	68.55	68.00	22.55	27.24
2	6.93	28.55	68.82	68.62	21.90	24.41
3	14.81	27.10	68.58	68.85	23.31	24.96

Table A 14: Activated Sludge, Membrane Diffuser, 200 L/min, mean values

Trial #	DO %		AmmoniumN [mg/L]		Nitrate [mg/L]	
	NTM	TM	NTM	TM	NTM	TM
1	20.90	37.66	69.32	69.47	24.40	25.64
2	22.62	30.61	69.80	70.44	25.23	26.28
3	16.66	34.437	70.84	71.567	25.81	27.377

Table A 15: Clean Water Test, Ceramic Diffuser, 70 L/min

Diffusor without TotalMix

					compressor on		
Cycle #	compressor on		compressor off		Power in	Power in	Energy
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	29	10.1	84	0	3569	4.78	29
2	24	9.9	81	0	3498	4.69	23
3	27	10.2	70	0	3604	4.83	27
4	28	10.2	67	0	3604	4.83	28
5	26	10.1	69	0	3569	4.78	26
6	27	10	71	0	3533	4.74	27
7	28	10.2	68	0	3604	4.83	28
	27		73		3569	4.78	27

Diffusor with TotalMix

					compressor on		
Cycle #	compressor on		compressor off		Power in	Power in	Energy
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	44	10	30	0	3533	4.74	43
2	41	10.1	29	0	3569	4.78	41
3	43	9.9	27	0	3498	4.69	42
4	46	10	27	0	3533	4.74	45
5	48	10	30	0	3533	4.74	47
6	45	10.2	28	0	3604	4.83	45
7	46	10.1	27	0	3569	4.78	46
	45		28		3549	4.76	44

Table A 16: Clean Water Test, Ceramic Diffuser, 140 L/min

Diffusor without TotalMix

					compressor on		
Cycle #	compressor on		compressor off		Power in	Power in	Energy
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	47	10	38	0	3533	4.74	46.13
2	35	10	46	0	3533	4.74	34.35
3	41	10	28	0	3533	4.74	40.24
4	34	10	29	0	3533	4.74	33.37
5	43	9.9	44	0	3498	4.69	41.78
6	42	9.9	31	0	3498	4.69	40.81
7	38	10.1	32	0	3569	4.78	37.67
	40		35		3528	4.73	39.19

Diffusor with TotalMix

					compressor on		
Cycle #	compressor on		compressor off		Power in	Power in	Energy
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	91	10	17	0	3533	4.74	89.32
2	97	10.1	16	0	3569	4.78	96.16
3	117	9.9	14	0	3498	4.69	113.69
4	78	10	13	0	3533	4.74	76.56
5	84	9.9	17	0	3498	4.69	81.62
6	89	10	18	0	3533	4.74	87.35
7	92	10.1	17	0	3569	4.78	91.20
	93		16		3533	4.74	90.84

Table A 17: Clean Water Test, Membrane Diffuser, 70 L/min

Diffusor without TotalMix

Cycle #	compressor on		compressor off		compressor on Power in	Power in	Energy
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	23	9.9	60	0	3498	4.69	22.35
2	27	9.8	78	0	3463	4.64	25.97
3	25	10.1	62	0	3569	4.78	24.78
4	20	10	60	0	3533	4.74	19.63
5	23	10.1	73	0	3569	4.78	22.80
6	22	9.9	54	0	3498	4.69	21.38
7	25	9.9	62	0	3498	4.69	24.29
	23.57	9.96	64.14	0.00	3518.24	4.72	23.03

Diffusor with TotalMix

Cycle #	compressor on		compressor off		compressor on Power in	Power in	Energy
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	48	10.2	36	0	3604	4.83	48.05
2	49	10.1	33	0	3569	4.78	48.57
3	47	10.1	31	0	3569	4.78	46.59
4	48	10.1	33	0	3569	4.78	47.58
5	49	10	34	0	3533	4.74	48.09
6	49	10.2	35	0	3604	4.83	49.06
7	48	9.9	34	0	3498	4.69	46.64
	48.29	10.09	33.71	0.00	3563.67	4.78	47.80

Table A 18: Clean Water Tests, Membrane Diffuser, 140 L/min

Diffusor without TotalMix

					compressor on		
Cycle #	compressor on		compressor off		Power in	Power in	Energy in
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	24	9.9	40	0	3498	4.69	23
2	33	9.9	49	0	3498	4.69	32
3	29	9.9	44	0	3498	4.69	28
4	31	9.9	44	0	3498	4.69	30
5	32	9.9	49	0	3498	4.69	31
6	29	9.9	44	0	3498	4.69	28
7	33	10	46	0	3533	4.74	32
	30		45		3503	4.70	29.34

Diffusor with TotalMix

					compressor on		
Cycle #	compressor on		compressor off		Power in	Power in	Energy in
	Time [sec]	Amp	Time [sec]	Amp	Watts	hp	kWh
1	57	9.8	26	0	3463	4.64	55
2	62	9.9	23	0	3498	4.69	60
3	65	9.8	22	0	3463	4.64	63
4	54	9.8	26	0	3463	4.64	52
5	57	9.9	24	0	3498	4.69	55
6	62	9.8	26	0	3463	4.64	60
7	58	9.8	23	0	3463	4.64	56
	59		24		3473	4.66	57.19