Institutionen för naturgeografi
och kvartärgeologi

Stockholms
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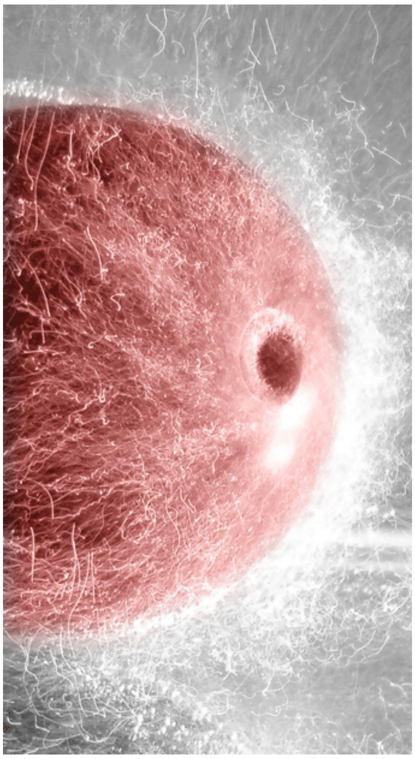
Efficiency of Watreco´s vortex generator in wastewater



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Examensarbete i miljöskydd och hälsoskydd
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Examensarbete av Pascale Ribordy

INSTITUTIONENS FÖRORD

Denna uppsats är utförd som ett examensarbete vid Institutionen för naturgeografi och kvartärgeologi, Stockholms universitet. Examensarbetet ingår som en kurs inom magisterutbildningen Miljö- och hälsoskydd, 60 högskolepoäng.

Examensarbetets omfattning är 15 högskolepoäng (ca 10 veckors heltidsstudier). Handledare för examensarbetet har varit universitetslektor Wolter Arnberg, Institutionen för naturgeografi och kvartärgeologi, Stockholms universitet.

Författaren är ensam ansvarig för examensarbetets innehåll.

Stockholm i maj 2011

Anders Nordström
universitetslektor, kursansvarig

Sammanfattning

Cleantech-företaget Watreco har genom nytänkande och ett innovativt synsätt utvecklat en vattenbearbetningsteknik som härmar naturen. Tekniken kallas för Vortex Process Technology (VPT) och bygger på en vortexgenerator. Genom att kombinera VPT med en pump kan vatten syresättas genom virvling. Den här studien genomfördes i testanläggningen vid Hammarby Sjöstadsverk. Avloppsvatten med låg syrehalt inluftades utan inblåsare eller kompressor. Syrets överföringshastighet (Standard Oxygen Transfer Rate, SOTR) för enheten i rent vatten uppmättes till 28.6 g/h medan syrets överföringseffektivitet (Standard Aeration Efficiency, SAE) uppmättes till 0.03 kg/kWh. Slammet i den aktiva slamprocessen har bättre sedimenteringsegenskaper efter virvling och luftning med vortexgeneratorn. Ytterligare tester krävs dock för att fastställa effektiviteten och hur slammets egenskaper påverkas.

Preface

The primary focus for this study was originally to determine if Watreco's Vortex Process Technology could contribute to reducing disinfection products in pool water with air. Chlorination of pool water is a common and efficient disinfection method. Chlorine gas is very reactive and produces a variety of disinfection side-products when it reacts with microorganisms, organic material and nitrogen compounds such as urine and sweat. Water and air samples before and after treatment of pool water with a vortex generator were to be analyzed for the common disinfection side-products trihalomethanes and chloramines responsible for swimming-pool-associated asthma and allergies. Unfortunately, after talking to several experts in the matter, it came to my knowledge it was difficult to measure trichloramines in air (Johanson 2010). The experts did not agree on the right method for analysis of the samples. The focus of the study was consequently shifted to study the vortex generator's effect on wastewater.

Many people have been engaged in this study and I would like to thank some of them especially. First of all I would like to thank the gang at Watreco and especially Curt Hallberg, Anders Ive and Johan Kronholm who gave me the possibility to carry out this project and opened the door to a new world for me. Gunnel Dalhammar (KTH) who assisted me throughout the study with enthusiasm and joy. Lars Bengtsson (IVL, Sjöstadsverket) for his help and input during the experiments. Wolter Arnberg (Stockholm University) my supervisor, sharing his experience and given me feedback on my study and report. Finally, Geneviève Ribordy and Claudette Asgarali Sing who have contributed to the linguistic part of the report and my family for the mental support.

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Introduction

Water has the possibility of cleaning itself through swirling as it does in streams. Natural way, nature's way! Watreco, a market driven research and innovation company in cleantech, works with frontline environmental technology, based on nature's own principles. With an innovative and sustainable approach under the principle "In harmony with nature", the company develops energy efficient products and systems for water treatment on a global market. The technology is called Vortex Process Technology (VTP) and is based on water's own natural movement. The vortex generator sets the water in a considerable swirl that changes its internal properties. In the swirling process, air is aspirated and consequently the water is aerated without the need for blowers or compressors.

The main purpose of this study was to determine if Watreco's vortex generator could be used to oxygenize anaerobic wastewater as well as anoxic/aerobic sludge and evaluated if the sludge properties were affected. An attempt was made to compare Watreco's vortex generator performance to other systems found in the literature.

A wastewater treatment plant purifies the water by first of all separating solids from liquids. Larger solids are removed from wastewater by grids and settling of suspended particles. Secondary, suspended and dissolved organic matters are removed in a biological process. Up to 85% of the remaining organic material is consequently removed by cultivating sewage microorganisms in the wastewater in an aeration tank (US EPA 1999).

In this wastewater treatment process, aeration introduces air into the liquid, thereby providing an aerobic environment for microbial degradation of organic matter. The purpose of aeration is: 1) to supply the required oxygen to the metabolizing microorganisms and 2) to provide mixing so that the microorganisms come into intimate contact with the dissolved and suspended organic matter (McCarthy 1982). Two aeration systems are common: mechanical and subsurface. A mechanical system agitates the wastewater, for example with blades, to introduce air. In a subsurface system, air is introduced by submerged devices in the wastewater in order to bring oxygen to biological reactions and keep solids in suspension (US EPA 1999). Many industrial solutions are available to provide aeration and many build on energy demanding compressors and blowers. Power costs associated with the operation of the aeration process generally run from 30 to 75 percent of the total electrical power used by a typical activated sludge wastewater treatment facility (Rosso *et al.* 2008, US EPA 1999, Powels Groves 1992). Most municipal wastewater use aeration due to its advantageous aeration efficiency meaning the mass of oxygen transferred per unit energy required (Rosso *et al.* 2008).

The concentration of dissolved oxygen in natural water and wastewater is a function of the temperature of the air and water, the degree of hardness of the water, and the demand for oxygen in the body of water. The solubility of oxygen increases with decreasing water temperature (oxygen solubility in water is inversely proportional to temperature). Dissolved oxygen concentration is an important parameter in wastewater treatment processes, most notably when dealing with an activated sludge system (ITT).

At lower dissolved oxygen content, the environment is not stable for the microorganisms due to anaerobic zones; the organisms at the center of the floc may die and consequently lead to the breaking up of the floc. Low dissolved oxygen concentration may also lead to the release of greenhouse gas nitrous oxide. However, high dissolved oxygen levels promote unwanted filamentous organisms and require higher energy demand (Emerson 2009, Bengtsson 2010, Renius 2010). Most plants maintain about 2 mg/l of dissolved oxygen in their activated sludge systems (Emerson 2009, Bengtsson 2010).

Standard Oxygen Transfer Rate (SOTR) measurements, Standard Aeration Efficiency (SAE) and Standard Oxygen Transfer Efficiency (SOTE) are useful to compare the performance of oxygenation devices in clean water and the energy efficiency (ASCE 2007, Åmand 2010).

Method

The experiments were carried out at the test facility for wastewater purification at Hammarby Sjöstadsverk. At the facility, it was possible to experiment on tap water, anaerobic water and aerobic activated sludge, to measure reoxygenation using Watreco's device and analyze the results. The method using a Dissolved Oxygen meter has been widely used to determine the efficiency of aeration devices (ASCE 2007, ASCE 1997, Emerson 2009).

The experiments were carried out as follows: The first five measurements were performed on tap water. The two types of wastewater used during the experiments were: Anaerobic water from the membrane biological reactor and settled aerobic water from the activated sludge process. The wastewater experiments were performed according to the following sequence: Anaerobic water (two series), activated sludge water (four series), anaerobic water (two series), and activated sludge water (one series).

Instruments

The experiments were carried out using Watreco VPT aerator prototype AE120. The vortex generator was connected with a 1.5 m hose to a submersible pump from Biltema, 900W, Hmax.: 36 m, Qmax.: 6 m³/h, Max. 35°C. The prototype was then tested in approximately 180 liter tap water, anaerobic wastewater and aerobic sludge water respectively in a 240 liter plastic container.

Measurement of oxygen transfer in clean water

Dissolved oxygen concentrations for Watreco's vortex generator were measured for tap water and the Standard Oxygen Transfer Rate (SOTR) was calculated. SOTR describes the mass of oxygen that is dissolved in a volume of water per unit time. The dissolved oxygen was removed from the tap water volume by adding 20mg sodium sulfite. The pump and the vortex generator were submerged in the water. The pump was turned on. The pump circulated water from the bottom of the aeration basin through the vortex generator in the middle of the basin. During the reaeration period the dissolved oxygen concentration and temperature of the water were monitored with an *in situ* membrane probe connected to a HQ-series portable meter (HQ40d). Measurements were recorded on a USB-memory stick every 10 seconds until saturation or for 30 minutes. The air intake was also monitored with an air-flow meter. The sequence was repeated four more times.

Measurement of oxygen transfer in anaerobic water

Anaerobic water from the Membrane Biological Reactor was filtered through a sand filter. A ventilation hose was placed above the container with the wastewater to remove the expelled gases. The vortex generator and the pump were submersed in the anaerobic water and the pump was turned on. The dissolved oxygen concentration and the temperature of the water volume were monitored and recorded every 10 seconds for 30 minutes. The air flow was also monitored. The sequence was repeated three more times.

The equipment was cleaned between each sequence: The pump and vortex generator were immersed in a large container filled with tap water, the pump was started and the water circulated through it for approximately 5 minutes. The dissolved oxygen probe was rinsed under running tap water.
During Sequence 4, the dissolved oxygen concentration and temperature were recorded, for technical reasons every 5 minutes during 22 hrs 45 min.

Ammonia and nitrite Lange analysis were done at 1, 10, 20 and 30 minutes for Sequence 1. Ammonia, nitrite and nitrate Lange analysis were done after 22 hrs 45 min for Sequence 4.

Measurement of oxygen transfer in aerobic activated sludge

For practical reasons, the activated sludge used during the experiments was taken from the settled sludge, which has a settling property of 90 percent. The vortex generator and the pump were submerged in the anoxic/aerobic sludge water and the pump was switched on. The dissolved oxygen concentration and temperature of the water volume were monitored and recorded every 10 seconds for 30 minutes to 1 hour. The air flow was also monitored. The sequence was repeated four more times. The equipment was cleaned in a similar fashion for five minutes between each sequence.

Wastewater samples of 1 liter were taken from Sequence 1, 2 and 3 after aeration with the vortex generator. The samples were allowed to settle and the sludge volume was noted after 15, 30 and 60 minutes.

Calculations

The Standard Oxygen Transfer Rate (SOTR [g/h]) was calculated for the sequences on clean water (Appendix A) and the Standard Aeration Efficiency (SAE) and Standard Oxygen Transfer Efficiency (SOTE) were then calculated for all sequences.

Every oxygen transfer system has an Oxygen Transfer Rate (OTR). The SOTR shows the hypothetical value of OTR under certain conditions, ie. water temperature is 20 °C, and the barometric pressure is 1.00 atm (101.3 kPa). Another assumption of the SOTR is that both temperature and dissolved oxygen (DO) concentration is uniform throughout the water volume, throughout the experiment.

Results

The results are reported in the same order as in the methods, though the results for tap water and anaerobic water are reported together and the results from the calculations are reported in direct connection to the sequences they refer to.

Measurement of oxygen transfer in anaerobic water compared to clean water

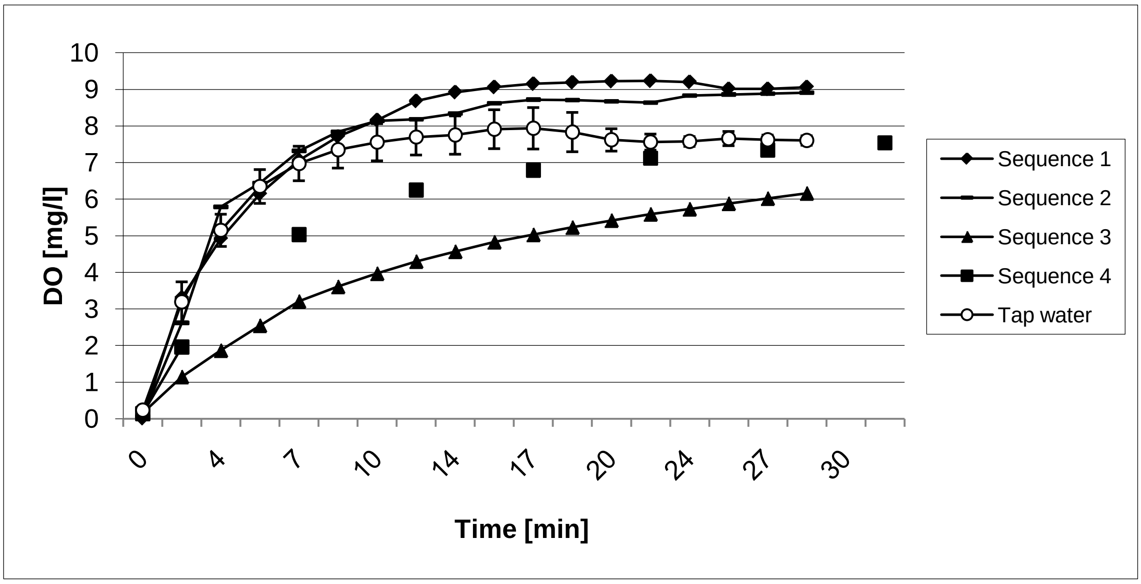

Figure 1. Dissolved oxygen concentration for four sequences in anaerobic wastewater compared to the dissolved oxygen concentrations for deoxygenated tap water (with standard deviation) aerated with Watreco's vortex generator over a period of 30 min.

The sequences were curve fitted to the oxygen concentration function (Appendix A, Eq.2) with non linear regression analysis. The estimated values are presented in Table 1 and Table 2 together with the SOTR, SAE result and SOTE calculations (Appendix A: Eq.2, Eq.3, and Eq.4).

Table 1. Results of the calculations according to Appendix A for the sequences in anaerobic wastewater aerated with Watreco's vortex generator.

	C^*_∞ [mg/l]	K_La [1/s]	R^2	V [l]	Flow air [l/min]	SOTR [mg/s]	SOTR [kg/h]	SAE [kg/kWh]	SOTE [-]
Sequence1	9.226	0.00379	0.9945	180	11.48	6.30	0.0227	0.0252	0.0274
Sequence2	8.753	0.00466	0.9904	180	11.48	7.34	0.0264	0.0294	0.0319
Sequence3	6.596	0.00144	0.9981	180	10.30	1.71	0.0062	0.0069	0.0083
Sequence4	7.588	0.00245	0.8373	180	11.48	3.35	0.0121	0.0134	0.0146
Tap water	7.420	0.00551	0.9968	180	11.48	7.36	0.0265	0.0294	0.0319

Sequence 1 and 2, carried out in the anaerobic water, showed similar dissolved oxygen concentrations increase as the tap water trials did (Figure 1). During Sequence 3, the dissolved oxygen concentration increased slower than in the other sequences. The air intake was lower during Sequence 3 than for the other sequences, approximately 10.30 l/min contra 11.48 l/min (Table 1). During Sequence 4, the dissolved oxygen values were recorded every 5 minutes for 22:45 hrs. The dissolved oxygen concentration increase was slower than for tap water and for Sequence 1 and 2, but after approximately 30 minutes of aeration with the vortex generator, the dissolved oxygen concentration had reached over 7.5 mg/l and remained between 7.5 and 8 mg/l for the rest of sampling period.

The results from the Ammonia and Nitrite Lange analysis for Sequence 1 gave approximately 40 mg/l Ammonia for all four analyses (at time 0, 10 min, 20 min and 30 min). After 22:45 hrs of aeration with the vortex generator (Sequence 4), the Ammonia was 37 mg/l, the Nitrite was 0.2 mg/l and the Nitrate 67 mg/l.

Measurement of oxygen transfer in aerobic activated sludge

The activated sludge water had been settled and was mostly anoxic before the experiments, with dissolved oxygen concentrations between 0,09 mg/l to 1,41 mg/l (Figure 2).

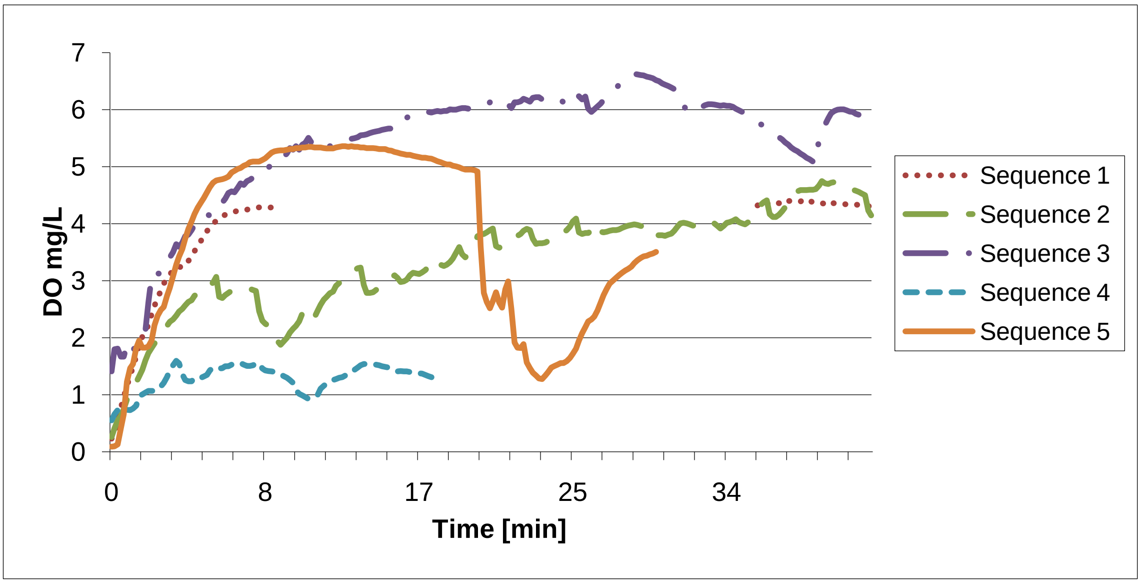

Figure 2. Dissolved oxygen concentrations for the five sequences in aerobic sludge water taken from activated sludge process which had been settled and then aerated with Watreco's vortex generator over a period of 30-60 min.

During every sequence carried out in the activated sludge, sludge particles were trapped in the pump's water intake, which was notable when pulling up the pump, but also by the decrease in air flow (Table 2).

The broken line for Sequence 1 is due to the fact that the dissolved oxygen-meter probe was trapped to the bottom of the basin during most of the sequence and was pulled up towards the end of the sequence. The air intake was above 10.3 l/min.

During Sequence 2 and Sequence 4, little movement through the pump and the vortex generator was noted as well as low air intake (Sequence 2: 3.2 l/min; Sequence 4: 5.5 l/min (Table 2)). Sequence 2 showed much higher dissolved oxygen concentrations than Sequence 4 (Figure 2). Sequence 4 was interrupted after 17.5 minutes due to technical problems.

During Sequence 3 and Sequence 5, the dissolved oxygen concentrations reached above 5.3 mg/l and remained there during Sequence 3 but decreased drastically for Sequence 5

(Figure 2). Air intake during Sequence 3 was above 7.3 l/min during the first 30 minutes and decreased down to 6.4 l/min. At the beginning of Sequence 5 the air intake was 11.4 l/min but then decreased to 4.6 l/min (Table 2). This sequence was stopped after 30 minutes.

Table 2. Results of the calculations according to Appendix A for the sequences in aerobic activate sludge with Watreco's vortex generator.

	C^*_∞ [mg/l]	K_La [1/s]	R^2	V [l]	Flow air [l/min]	SOTR [mg/s]	SOTR [kg/h]	SAE [kg/kWh]	SOTE [-]
Sequence1	4.398	0.00646	0.9940	180	10.30	5.11	0.0184	0.0205	0.0247
Sequence2	4.334	0.00121	0.7844	180	3.2	0.95	0.0034	0.0038	0.0148
Sequence3	6.062	0.00308	0.9345	180	6.4	3.36	0.0121	0.0134	0.0262
Sequence4	1.418	0.00931	0.4964	180	5.5	2.38	0.0086	0.0095	0.0215
Sequence5	4.067	0.00999	0.2688	180	4.6	7.32	0.0263	0.0293	0.0793

Aeration efficiency and sedimentation

Table 3. Comparison of Standard Aeration Efficiency (SAE) in clean water for Watreco's vortex generator to values in the literature (EPA 1984, Bolles 2006, Technical Bulletins 2003, Corel *et al.* 2003)

Aeration System	**SAE kg/kWh**
Watreco	0.03
Diffused Aeration	
Fine Bubble Diffusers:	
- Advanced Technology Membranes	7.30
- Ceramic Disk or Dome Grid	3.04-4.26
Course Bubble Diffusers	1.22-2.13
Combination Systems:	
- Jet Aeration (pumps and compressors)	1.22-2.13
- Submerged Turbines (turbines and compressors)	0.91-1.52
Surface Mechanical Aerators: - Rotors	1.52-2.13

Watreco's vortex generator has shown a relatively low Standard Aeration Efficiency value of 0.03 kg oxygen per kWh, while mechanical aeration systems such as rotors showed SAE values between 1.52 and 2.13 kg/kWh, combination systems between 0.91 and 2.13 kg/kWh and diffused aeration systems between 1.22-7.30 kg/kWh.

Table 4. Volume (ml) of the sludge after 15, 30 and 60 minutes of sedimentation from samples taken from the aerobic activated sludge before and after 60 minutes aeration with Watreco's vortex generator.

Sequence #	ml after 15 min	ml after 30 min	ml after 60 min
before	n/a	900*	n/a
1	450	400	300
2	700	460	360
3	220	160	140

* information provided by Sjöstadsverket (Bengtsson 2010)

The activated sludge wastewater, directly from the process, settled to approximately 900 ml in 30 minutes. After aeration and swirling of the sludge water with the vortex generator, settling was below 500 ml after 30 minutes (Table 4).

Discussion

The aeration systems are often the largest energy consumer at a water purification plant (Reardon 1995). Large savings could be obtained by reducing the energy demand of the aeration system.

Standard Oxygen Transfer Rate measurements are useful for comparing the performance of oxygenation devices operating in clean water, while the SAE is useful in comparing the energy efficiency. However, comparing SOTR values for different aerators is only relevant under very similar conditions of pump type and power, water volume and experimental setup. In order to produce comparable figures, different systems should be run in parallell under the same conditions. Such tests have been beyond the scope of this study.

The SAE value is compensated for energy usage, which makes it more suitable for comparing different types of aerators. However, it is hard to find published SAE values, and the exact experimental conditions are rarely given. For example, the SAE value found in Corel *et al.* (2003) is 0.8 and 2.4 kg/kWh, while that of this study is 0.03 (Table 3). This indicates that the membrane aerator is better than the present system. It should be remembered though that this system is an unoptimized prototype of a very different approach to aeration. It is not expected to perform better than commercially available aerators at this point. From this perspective, the performance is actually showing interesting and promising results.

The oxygen requirement for wastewater is different from clean water. In order to compare aeration system equipment, the relative rate of oxygen transfer in wastewater compared to clean water must be established which is known as the alpha value (Bolles 2006). However, the performance of the devices in wastewater may differ largely depending on the function of the device, how it is used and the nature of the processed water (ASCE 2007). The effects of contaminants on the alpha factor must be evaluated on a case-by-case basis. The varying nature of many municipal and industrial wastewater as well as water temperature, turbulence and aeration methods causes large fluctuations in the alpha factors (US EPA 1983). Consequently, more research and testing is required to determine the Alpha value for the vortex generator in different types of wastewater.

The anaerobic wastewater was treated in the Membrane Biological Reactor for a period of 2.5 hrs and was then filtered through a sand filter. Consequently, the sand-filtered wastewater used for the experiments had no dissolved oxygen. Watreco’s vortex generator is a subsurface aeration system which contributed to agitate and aerate the wastewater. The vortex generator oxygenizes the anaerobic wastewater in a similar way to the tap water. After 30 minutes of aeration with the vortex generator, the dissolved oxygen was approximately 9 mg/l (Figure 1, Table 1).

Lower aeration and lower dissolved oxygen concentration were noted during Sequence 3 and 4 in the anaerobic wastewater (Figure 1, Table 1). The sequences were carried out after the pump and the vortex generator had been used to aerate activated sludge water. Although the pump and vortex generator were cleaned in between sequences, it is possible that thicker material was clogging the pump and thereby reducing the amount of water being pumped through the vortex. More efficient cleaning of the pump would have been required.

Nitrification bacteria required more than thirty minutes of swirling and aeration with the vortex generator to start nitrifying. After 22 hours, the nitrification process had started. From these results, it is not possible to determine whether the aeration alone had an effect on these bacteria. More testing is required to determine the time required for the nitrifying bacteria to start metabolizing and to establish the contribution of the vortex movement.

At Sjöstadsverket, the aerobic activated sludge process is activated with an air compressor controlled by a dissolved oxygen meter, maintaining a dissolved oxygen concentration between 2.0-2.5 mg/l. This is sufficient for the bacteria, high enough to prevent nitrous oxide production and keeping the energy demand low (Bengtsson 2010). The goal is not for the dissolved oxygen values to reach 100% saturation. During the experiments, the pump connected to Watreco’s vortex generator ran constantly at maximum power which could explain the observation of the wide range of dissolved oxygen concentrations, although all sequences reached above 2 mg/l (Figure 2). By connecting the vortex generator to a dissolved oxygen controlled pump it would be possible to obtain a more stable dissolved oxygen value and consequently meet the same values as the existing system and consequently lowering energy demands of the system.

The pump used with the vortex generator seemed to be a limiting factor, having material partly clogging the pump. The variation in the dissolved oxygen concentration during and between the various sequences (Figure 2) seems to depend on the amount of organic material that fastened to the pump: When the material fastened, less water was pumped through the vortex generator and consequently less air was sucked in. It seems that the pump was still partly clogged when Sequence 3 and 4 began, since the dissolved oxygen curve was flatter than during Sequence 1 and Sequence 2, this can also be confirmed by the low air intake at the beginning of Sequences 3 and 4 (Table 2). The wastewater used during the experiment was thicker than the water used in the activated sludge process since it was taken from the settled sludge. Consequently, with a better pump and water with lower viscosity, the vortex generator could give stable and similar aeration results as the compressor used by Sjöstadsverket. Despite the partial clogging of the pump during Sequence 3, it seems that air intake above 6 liter air/min provided sufficient aeration to maintain a high dissolved oxygen concentration of the active sludge (Figure 2, Table 2).

A commonly used method for measuring wastewater oxygen transfer efficiency is off-gas analysis (Renius 2010). The method measures the change in oxygen content of the air entering and the off-gas exiting the aeration tank (Powell Groves 1992). The method described by Redmon *et al.* (1983) and US standard ASCE-Standard 18-96 (1997) and used by the U.S. EPA should be considered when further testing the vortex generator.

Aeration with the vortex generator seemed to increase the settling properties of the sludge (Table 4). This effect may be the results of the vortex movement and aeration, simultaneously causing both a high shear rate and gas exchange in the liquid and contributed to the agglomeration or deagglomeration of the sludge. An indication that this might be the case appears when comparing Sequence 2 to Sequence 3: The activated sludge was swirled and oxygenated more actively during Sequence 3 than during Sequence 2 (Figure 2) and the settling properties were also much better (Table 4). Municipal wastewater treatment plants worldwide have regular problems with bulking sludge often due to extensive growth of filamentous bacteria at the detriment of the floc-forming bacteria (Jonsson 2005). Further testing of the effects of the vortex generator on the sludge is required to confirm its positive effects which could potentially replace the commercially used solutions such as ozone, synthetic polymer, hydrogen peroxide etc.

Conclusions

This study has permitted to come to the following conclusions:

- Watreco's VPT prototype oxygenates anaerobic and aerobic/anoxic wastewater.
- The Standard Aeration Efficiency for the presently used VPT prototype was lower than the values found in the literature.
- The nitrification processes in the anaerobic wastewater were activated after swirling and aeration with the VPT prototype.
- The improved settling properties of the activated sludge after treatment with the VPT prototype is a very interesting result

In order to further improve the aeration efficiency of the presently used system, a good balance has to be found between water volume, pump design and effect, and the size and design of the system. Further experiments with the vortex generator in wastewater would allow for more accurate determination of the effects of VPT prototype treatment on both aeration efficiency and sludge properties.

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Appendix A. Calculations

(ASCE 2007)

The model that describes the oxygen concentration is:

$$C(t) = C^*_\infty - (C^*_\infty - C_0) \cdot \exp(-K_La \cdot t) \quad \text{(Eq.1)}$$

where

$C(t)$ is the DO concentration at a given time,

C^*_∞ is the steady-state DO concentration as time approaches infinity,

C_0 is the DO concentration at time zero,

K_La is the volumetric mass transfer coefficient.

The constants above are estimated by non-linear regression based on the sampled values of the DO concentration. At every determination (sampling) point, the K_La and the C^*_∞ are corrected automatically to standard conditions (20°C, 101 kPa) by the instrument (Hach–Lange HQd40, LDO10101).

Standard oxygen transfer rate, SOTR:

$$SOTR = V \cdot K_La_{20} \cdot C^*_{\infty 20} \quad \text{(Eq. 2)}$$

where V is the liquid volume in the test tank,

K_La_{20} is the volumetric mass transfer coefficient corrected to 20°C,

$C^*_{\infty 20}$ is the steady-state DO concentration as time approaches infinity corrected to 20°C and 101 kPa.

Standard oxygen aeration efficiency, SAE:

$$SAE = SOTR / \text{Power input} \quad \text{(Eq.3)}$$

Standard oxygen transfer efficiency, SOTE

$$SOTR = SOTR / W_{02} \quad \text{(Eq.4)}$$

where

W_{02} is the mass flow of oxygen in air stream.