Energy improved aeration at Sternö wastewater treatment plant

ABSTRACT

The objective of this study was to improve energy efficiency of a mid-size wastewater treatment plant by upgrading the aeration system and controls. One of two treatment lines at the plant were upgraded with a new blower, aeration grid and process controls while the other line was kept intact with existing equipment installed during the plant construction in 1997. The existing aeration system consisted of a lobe blower and tube diffusers and was controlled by DO control. In the upgraded line, the aeration system consisted of a screw blower and Sanitaire Silver Series Low Pressure diffusers. It was controlled with a Sanitaire aeration control system consisting of cascade DO control, ammonia feedback control and most open valve logic. In addition, the DO profile was adjusted to the current load at the plant. The two lines were operated in parallel from September 2011 to June 2012 and their operation was monitored with lab samples and online probes for evaluation of energy consumption and treatment performance. The 10 month long comparison showed a reduction in energy consumption in the upgraded line with 66 % compared to the existing line. The airflow required was reduced with 35 %. With these savings, the field aeration efficiency (measured as kg O2/kWh) was close to three times as high in the upgraded line as in the existing line. These large energy savings were a combined result of the more energy efficient blower as well as a higher oxygen transfer efficiency and lower pressure loss of the new aeration grid. The Sanitaire process control system further decreased the energy consumption with a tighter and more accurate DO control, reduced pressure losses with the most open valve logic and a more efficient use of the aerated volume with the new DO profile. Improvements were also seen on the treatment performance with an on average 9 % higher ammonia reduction in the upgraded line compared to the reference line. The largest difference was seen during the cold water period during which the nitrification was reduced at the plant. During this period, the ammonia reduction was 16 % higher in the upgraded line.

KEY WORDS

Nitrogen removal, Aeration control, Energy savings, Fine bubble diffusers

INTRODUCTION

Nitrogen removal trough nitrification and denitrification in an activated sludge process is a commonly used technology in wastewater treatment plants today. The process is energy demanding due to the oxygen requirement of the nitrification process. For each mg of ammonia nitrified, 4.6 mg of oxygen has to be supplied and transferred to the water. According to Olsson (2008) and Ingildsen (2002), the most energy consuming step of a wastewater treatment plant is the biological secondary treatment. This is mainly due to the energy demand of aeration. In fact, aeration alone generally calls for between 50 to 80 % of the total energy requirement of a wastewater treatment plant.

As the energy cost for the wastewater treatment industry rises and sustainability directives set new demands on carbon footprint reduction, the incitement for treatment plants to upgrade their aeration systems to reduce energy consumption is growing. At the same time, tougher effluent requirements cause higher oxygen requirements of treatment plants and increase the need for an efficient and optimized process.

The oxygen to the biological secondary treatment is often supplied to the water by a blower and a submerged aeration grid. The blower operates against a high system pressure mainly caused by the water column above the aeration grid, but also by pressure losses over the membranes and in the piping system. High pressure losses in the system cause a high energy demand for the blower. In addition, only a fraction of the oxygen in the air supplied by the blower is actually transferred to the water while the rest is lost to the atmosphere above the water surface. With the choice of an aeration grid with low pressure losses and high oxygen transfer efficiency, the energy consumption for aeration can be reduced significantly.

Besides the choice of blower and aeration equipment, the energy consumption of aeration is dependent on how the process is controlled. While the equipment choices reduce the energy required to supply a certain amount of oxygen, the control system will make sure that the correct amount of oxygen is supplied to meet the load requirement without wasting unnecessary energy.

The objective of this study was to reduce the energy consumption of a full scale wastewater treatment plant by upgrading the aeration system with new equipment and new controls. The upgrade was done based on combined knowledge of how to design aeration equipment for high energy efficiency, as well as for how to control and operate it in an efficient way.

MATERIAL AND METHODS

Field test site

The full-scale evaluation was conducted at Sternö wastewater treatment plant (WWTP), placed in southern Sweden. The plant was built in 1997 and is designed for 26000 population equivalents (pe), based on 70 g BOD/p/d. In 2010, only 17800 pe was connected to the plant. Effluent requirements for the plant are monthly average limits of 10 mg/l BOD and 0.5 mg/l Tot-P, as well as a yearly average limit of 12 mg/l Tot-N.

The plant consists of preliminary, primary and secondary treatment. A pre-denitrification process is used in the secondary treatment step, which is designed according to the Modified University of Cape Town (UCT) process with one anaerobic, one anoxic and one aerobic basin. The aerobic basin is divided into three zones, each containing one aeration grid. A mixer is installed in the first zone, making it possible to use this zone aerobic or anoxic depending on the nitrification capacity of the system. For control purposes the three aerated zones can be viewed as two since the first two zones are controlled from a common butterfly valve and actuator. For this reason, the first two zones will in this article be called zone 1 while the third zone will be called zone 2.

Compared treatment lines

The secondary treatment process at Sternö WWTP is divided into two identically sized separate treatment lines with a depth of 5.5 m. During the study, these were run in parallel and compared in terms of treatment performance and aeration efficiency. The air supply to the two lines was completely separated by a valve so that each line was supplied by its own blower(s).

One of the lines was used as a reference line with the existing aeration equipment and controls kept intact. This line was equipped with conventional lobe blowers and tube diffusers installed during the construction of the plant in 1997. The reference line aeration system was controlled from two DO probes, each controlling the valve position of the respective butterfly valve of the two zones. The control was done directly from the DO value to the valve position without cascade control of the airflow. DO set points used were 1.7 mg/l in zone 1 and 0.7 mg/l in zone 2. The blowers which supplied the reference line were run at a constant air pressure.

The second treatment line was used as a test line and was upgraded with new aeration equipment, instrumentation and controls. New Sanitaire Silver Series Low Pressure diffusers were installed in all three aerated zones and were supplied by an Atlas Copco ZS 45 + VFD screw blower. The new diffusers were installed with roughly the same diffuser density as in the reference line.

A Sanitaire aeration control system was used to control the test line. Based on a DO probe in each zone, a cascade control system using two PI controllers adjusted the position of butterfly valves. The cascade control consisted of an inner control loop, controlling the airflow supplied to each zone, and an outer control loop controlling the DO concentration. The purpose of using cascade control is to counteract the non-linear characteristic of valves, such as butterfly valves, as well as achieving a more stable control with quicker response to disturbances. The DO set points were adjusted compared to the reference line and were initially set to 0.7 mg/l in zone 1 and 1.0 mg/l in zone 2.

The new blower, diffusers and DO control system were all operating together for the first time in the beginning of September 2011. At the end of October 2011, the Sanitaire aeration control system was further upgraded with ammonia feedback control. The purpose with the ammonia feedback was to keep a stable effluent ammonia concentration despite the variable influent load by adjusting the DO setpoint. Ammonia was measured online in zone 2, and the measurement was used to control the DO setpoint for zone 1. Limits were set on minimum and maximum values allowed for the DO setpoint. The DO setpoint in zone 2 was kept at a fixed value in order to avoid disturbances of the denitrification in the anoxic zones. The control system is illustrated in Figure 1.

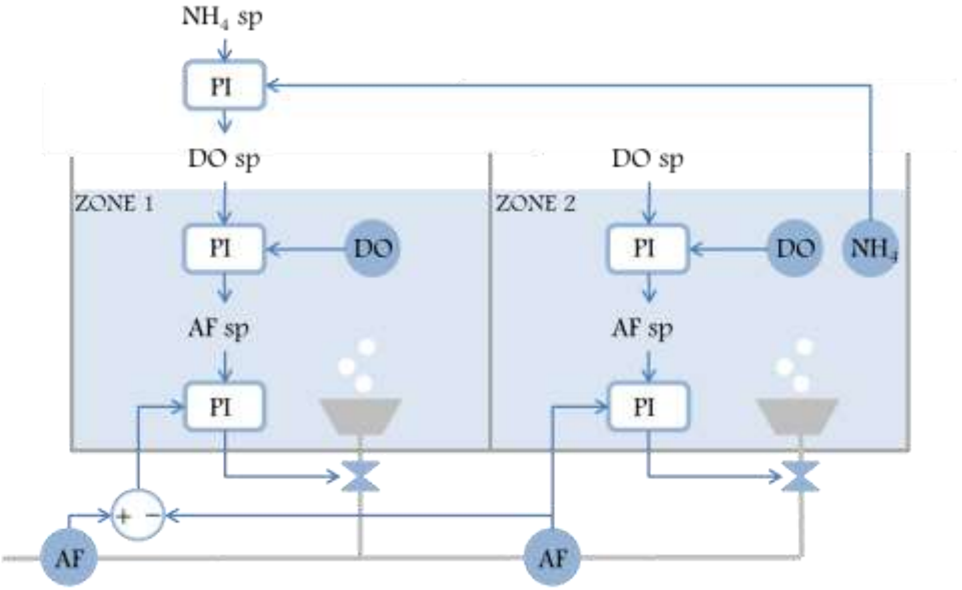

Figure 1: Sanitaire aeration control system layout implemented in the test line

The Sanitaire aeration control system in the test line also included most open valve (MOV) logic, which adjusted the manifold pressure based on the position of the valves by calculating pressure set points for blower control. With the MOV logic, the valves were kept as open as possible to minimize the pressure loss in the system, but at the same time never completely open in order to ensure control flexibility.The position of the valves in the test line was targeted to 75 to 95 % open. Automatic fouling prevention was also implemented with an air bumping system which increased the airflow for 5 minutes every week to stretch the membrane and break potential biofilm.

Evaluation period

The aeration system in the test line was installed in steps during 2011. The new screw blower was installed in April, the diffusers in July and the Sanitaire aeration control system was installed and tuned in September. The two lines were then operated in parallel and monitored until the end of June 2012, resulting in an evaluation period of 36 weeks.

During the study, both lab and online measurements were taken on various positions at the plant. Both treatment lines were monitored by ABB airflow meters and WTW online probes measuring DO, ammonia and nitrate according to Figure 2. On a weekly basis, composite samples were gathered from the inlet to each biological treatment line and the outlet of each secondary sedimentation basin. The samples were analysed in regards of BOD_7 and NH_4-N. The flow to each line was determined based on on-line measurements of the combined influent flow. For the evaluation of energy efficiency, the power consumption of each blower was monitored.

To ensure a fair comparison of the aeration systems, the treatment plant operators aimed to run the two treatment lines in the same way regarding all parameters except the aeration. During the study, the sludge age was on average 10.5 days in the reference line and 9.6 days in the test line.

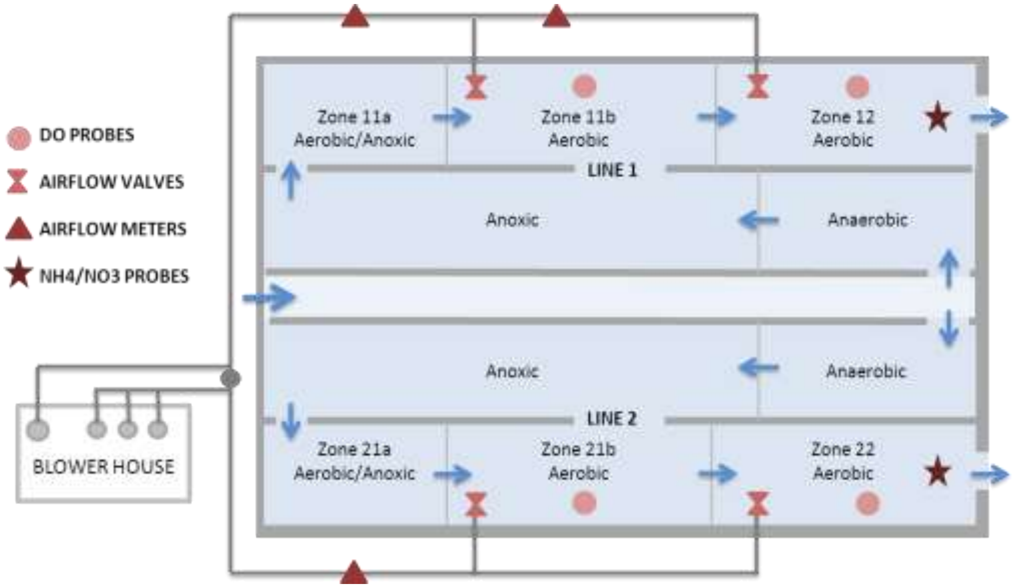

Figure 2: Process setup and on-line measurements in the test line (line 1) and the reference line (line 2)

Calculation of oxygen transfer and aeration efficiency

The mass of oxygen transferred to each line were calculated based on the BOD and ammonia reduction as well as the excess oxygen concentration according to ASCE (1996):

$$OTR_f = \left(X \cdot BOD_{5,r} + Y \cdot NH_4 - N_r\right) \cdot \left(\frac{\beta \cdot C_\infty^*}{\beta \cdot C_\infty^* - DO_f}\right) + Q \cdot DO_f \qquad (1)$$

where

- OTR_f = Oxygen transfer rate in field conditions, kg O_2/day
- X = Oxidation coefficient for BOD_5, kg O_2/kg BOD_5
- Y = Oxidation coefficient for NH_4-N, kg O_2/kg NH_4-N
- BOD_{5r} = BOD reduction, kg/day
- NH_4-N_r = NH_4-N reduction, kg/day
- β = Process water C^*_∞ / Clean water C^*_∞
- C^*_∞ = DO saturation at temperature T, mg/l
- DO_f = DO in field conditions, mg/l
- Q = Flow through each line, m^3/day

The values used for the oxidation coefficients were 1.2 for X (EPA, 1989) and 4.57 for Y (Metcalf &Eddy, 2003). The factor β was set to 0.95, according to ASCE (1996). All lab results of BOD_7 were converted to BOD_5 with the assumption that BOD_5 equals BOD_7/1.15 (Norrström, 1976).

The oxygen transfer rate was used to calculate the field aeration efficiency of each line, according to:

$$AE_f = \frac{OTR_f}{P} \qquad (2)$$

where

- AE_f = Aeration efficiency in filed conditions, kg O_2/kWh
- P = Power consumed by blower(s), kWh/day

Based on the aeration efficiency of each line, the difference in energy consumption between the treatment lines was calculated according to:

$$E_{red} = 100 \cdot \left(1 - \frac{AE_{f,ref}}{AE_{f,test}}\right) \qquad (3)$$

where

- E_{red} = Energy reduction , %
- $AE_{f,ref}$ = Reference line aeration efficiency in field conditions, kg O_2/kWh
- $AE_{f,test}$ = Test line aeration efficiency in field conditions, kg O_2/kWh

With this method, the difference in treatment performance was taken into consideration when comparing the energy consumed. In the same manner, the difference in required airflow between the lines were evaluated in terms of airflow per mass of oxygen transferred in order to take into account the difference in treatment performance between the lines.

RESULTS AND DISCUSSION

Energy consumption and aeration efficiency

During the 36 weeks of which the two aeration systems were operated in parallel, the energy consumption in the test line was on average 66 % lower than in the reference line. As can be seen in Table 1, the savings were relatively constant during the whole test period. Due to missing blower power data for a large part of May, this month is not included in the analysis. The required airflow was reduced with on average 35 % for the test line compared to the reference line. The month by month data in Table 1 show that the largest airflow savings were gained during February to April, which is when the water temperature was the lowest.

Table 1: Energy and airflow reduction from September 2011 to June 2012 for each month as well as average over the whole period

Period	Energy reduction [%]	Airflow reduction [%]
September 2011	63	29
October 2011	66	31
November 2011	62	25
December 2011	68	34
January 2012	64	30
February 2012	69	43
March 2012	69	42
April 2012	64	40
June 2012	69	35
Average, whole period	66	35

For the whole evaluation period, a large increase of the field aeration efficiency was measured in the test line compared to the reference line. The mean value of the field aeration efficiency in the test line and the reference line was 2.6 and 0.9 respectably, as can be seen in Table 2. This means that on average close to three times more oxygen was transferred to the water for each kWh in the new aeration system compared to the old one.

Table 2: Field aeration efficiency of the test and reference line from September 2011 to June 2012 for each month as well as average over the whole period.

Period	AE_f, test line	AE_f, reference line
September 2011	2.2	0.8
October 2011	2.2	0.7
November 2011	2.0	0.8
December 2011	2.7	0.8
January 2012	3.5	1.3
February 2012	3.0	0.9
March 2012	3.2	1.0
April 2012	2.8	1.0
June 2012	1.5	0.5
Average, whole period	2.6	0.9

The large energy savings were a combined result of all improvements done to the aeration system. A large part of the airflow reduction is due to the higher oxygen transfer efficiency of the new aeration system. With higher oxygen transfer efficiency, a larger percentage of the supplied oxygen from the blowers is transferred to the water, meaning that less air has to be supplied from the blower to reach a certain DO set point. Also contributing to the airflow reduction is the implementation of DO cascade control and a new DO profile with the Sanitaire process control system. While the DO cascade control provided a more stable DO level, the adjusted DO profile ensured a more efficient use of the whole aerated volume. When the new aeration system was first operated with the same DO profile as in the reference line, problems with high DO concentrations in zone 2 occurred since most of the nutrients were treated in the first zone. Adjusting the DO profile moved the load further down the basin and meant that the whole aeration volume was used more efficiently for nitrification.

The energy savings were also induced by a reduction in system pressure. After installing the new diffusers in the test line in June 2011, the pressure in the aeration system was decreased with 10 kPa to range between 57 and 60 kPa instead of the previous pressure of 70 kPa. The pressure reduction was a direct effect of lower pressure losses in the new aeration grid. The lower operating pressure decreased the energy consumption required by the blower to supply a certain amount of air. Implementation of MOV logic in the test line also reduced the system pressure since the adjustment of the air pressure minimized the losses over the valves. In the reference line, the constant air pressure had to be set sufficiently high to supply top loads, causing unnecessary energy consumption at low loads.

Besides the airflow and pressure reduction, a part of the energy reduction was a direct effect of the implementation of a more efficient blower. This measure directly decreased the power required to supply a certain amount of air at a set pressure.

Treatment performance

The nitrification is generally greatly affected by the water temperature, which could be seen at Sternö WWTP. While the summer months, with water temperatures around 16°C, usually provide almost complete nitrification at the plant, the nitrification capacity is reduced during the winter period when the water temperature is as low as 8°C. Since the study was conducted during both warm and cold water months, the effect of the new aeration system on the nitrification could be monitored and evaluated.

After the implementation of the new aeration system, improvements were seen in the reduction of ammonia as can be seen in Figure 3. During the warmer water periods, September to December as well as May and June, both lines achieved close to 100 % ammonia reduction. No difference could be measured on the ammonia reduction in the test line compared to the reference line. However, the cold water during January to April caused a significant drop in the ammonia reduction. Even though the test line also showed a decrease in treatment performance, the decrease is significantly lower than in the reference line. On average, an improvement on the ammonia reduction of 9 % was measured for the whole period. For the colder water months only, from January to April, the average ammonia reduction level was 72 % in the test line and 62 % in the reference line, resulting in an average increase of 16 %. The average effluent ammonia concentration during this period was 4 mg/l in the test line and 6 mg/l in the reference line.

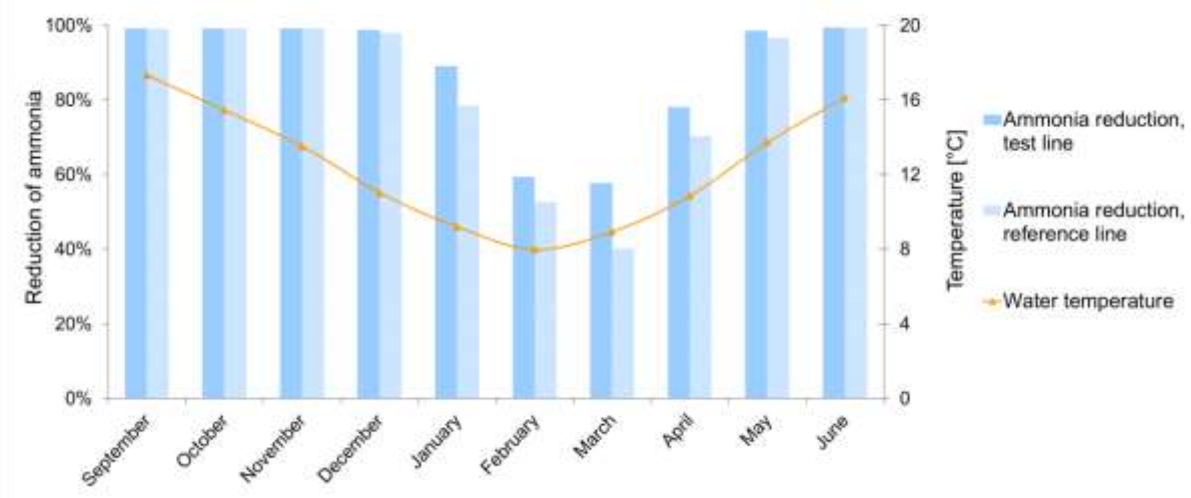

Figure 3: Ammonia reduction for the test and reference line as well as water temperature for the period September 2011 to June 2012

This difference is an effect of the improved aeration system as well as the fact that a higher DO level was kept in the test line as a result of the implementation of ammonia feedback control. During the cold water periods, fixed DO set points of 1.7 / 0.6 mg/l in zone 1 and 2 were used in the reference line. In the test line, a fixed DO set point of 0.7 mg/l was used in zone 2, while the DO set point in zone 1 was adjusted based on the measured ammonia concentration. During a large part of the cold water period, this set point was set to 2.5 mg/l. The suspended solids concentration was the same in both lines.

The ammonia feedback control in the test line did not however manage to keep the effluent ammonia as low as the desired setpoint of 1 mg/l during these months. The reason is that a high limit for DO, set to 2.5 mg/l, was reached, limiting the controller from further adjusting the process. This indicates that the reduced nitrification at Sternö WWTP during the winter months wasn't limited by DO alone. While the ammonia controller improved the nitrification to a certain degree, further improvements could only have been gained by also adjusting other limiting parameters such as aeration volume, MLSS concentration or sludge age. During the warm water months, the high ammonia reduction gave effluent ammonia concentrations close to 0 mg/l, despite the ammonia feedback setpoint of 1 mg/l. During this period, the low load to the plant caused the ammonia controller to instead be limited by the low limit set for DO in the controller.

The results illustrate that although the ammonia feedback did contribute to the increased ammonia reduction, DO must be the main limiting factor in order to successfully control on this parameter alone. In cases where DO is not the main limiting factor, ammonia feedback control could be combined with control of other process parameters such as sludge age or aeration volume to further improve the treatment results.

Unlike the reduction of ammonia, the BOD reduction was high in both lines during the whole evaluation period and no significant difference was seen between the two lines. The BOD reduction was on average 95 % on both lines during the evaluation period.

CONCLUSIONS

In this full scale study, one of two treatment lines was upgraded with new aeration equipment and control system. Its performance was compared to the existing aeration system in the other line in terms of energy efficiency and treatment performance.

The comparison showed large energy savings as a combined effect of improvements done to the aeration system. The new blower reduced the energy required to supply a certain amount of air. The new aeration grid provided higher oxygen transfer efficiency and a lower pressure loss, resulting in a lower air requirement for transferring a certain amount of oxygen to the water and a lower system pressure for the blower to operate against. The new control system reduced the airflow requirements with a tighter and more accurate control of DO as well as a DO profile that used the whole aerated volume more efficiently. In addition, MOV decreased the system pressure of the aeration system, which further increased the energy savings.

In total, the upgrade reduced the energy consumption with 66 % and the airflow requirement with 35 %. The field aeration efficiency was close to three times as high in the updated treatment line compared to the existing, meaning that three times more oxygen was transferred in the upgraded line per kWh.

Besides large energy savings, the upgraded treatment line also showed improvements on the ammonia reduction, which on average was 9 % higher than the existing line. The improvement was seen during the cold water periods, when the plant experience reduced nitrification and ammonia removal. A higher DO level was used in the upgraded line during this period as a result of the implementation of ammonia feedback.

These results clearly show that large energy savings are possible with the upgrade of aeration equipment and controls. Since aeration generally calls for a large part of a plant's total energy consumption, reductions in the energy required for the aeration will have a large effect on the total energy consumed at the plant. In this case, reducing the energy consumption for aeration in one of two lines with 66 % resulted in a decrease of the total energy consumption at the plant with 13 %. The results also demonstrate how upgraded aeration equipment and controls can stabilize the treatment process to give improved treatment performance.

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