Sustainability through Automation of Wastewater Treatment

A case study on the energy impacts of aeration control in parallel treatment lines

ABSTRACT

As energy prices rise and effluent quality regulations tighten across the country, many wastewater treatment plants turn to automating their control strategy in order to maximize the efficiency of their existing process and equipment. Upgrading controls can help a WWTP consistently meet more stringent effluent requirements, thereby avoiding expensive equipment upgrades or discharge fines.

The goal of the pilot study was to improve energy efficiency by upgrading the mechanical equipment and the electrical controls in one treatment line, while maintaining the existing equipment and controls in the reference line in an effort to compare effluent quality and energy consumption between the lines. The process controllers that were used to optimize the system include a cascaded DO control loop, most open valve control, and an ammonium feedback controller.

The data analysis showed an average energy reduction of 66% when combining the savings from both the mechanical equipment and process controls upgrades. Upon comparison of the two different DO control strategies, the upgraded controls provided a more stable and tighter control of the process variable around the setpoint. Additionally, with the ammonium control strategy, the variable DO setpoint resulted in an average 9% reduction in effluent ammonia for the period of analysis.

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. The most energy consuming step of a wastewater treatment plant is the biological secondary treatment and in fact, aeration alone generally accounts 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, the incitement for treatment plants to upgrade their aeration systems to reduce energy consumption is growing. At the same time, more stringent effluent requirements result in higher oxygen requirements and increase the need for an efficient and optimized process.

The oxygen to the biological secondary treatment is often supplied to the process 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. By selecting 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 process control system assures that the correct amount of oxygen is supplied to meet the load requirement without wasting unnecessary energy.

The objective of the pilot 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.

Site Background

The evaluation was conducted at Sternö WWTP, located in southern Sweden; a treatment plant built in 1997 and designed for 26,000 PE. In 2010, the current load was 2741 lb/d (1246 kg/d). Effluent requirements are 10 mg/l BOD and 0.5 mg/l TP as monthly average, and 12 mg/l TN as yearly average. The design is a typical conventional pre-denitrification activated sludge plant that consists of two treatment lines. Each line has one anaerobic, one anoxic and one aerobic basin. Each aerobic basin consists of three aerobic zones (see Figure 1). A mixer is installed in the first aerobic zone (Zones 11a and 21a in Figure 1) in each line, making it possible to use this zone as a swing zone (aerobic/anoxic). Furthermore, each aerobic zone has one aeration grid, i.e. in total three grids per line. For control purposes, the three zones can be viewed as two since the first two zones are controlled from the same valve and actuator.

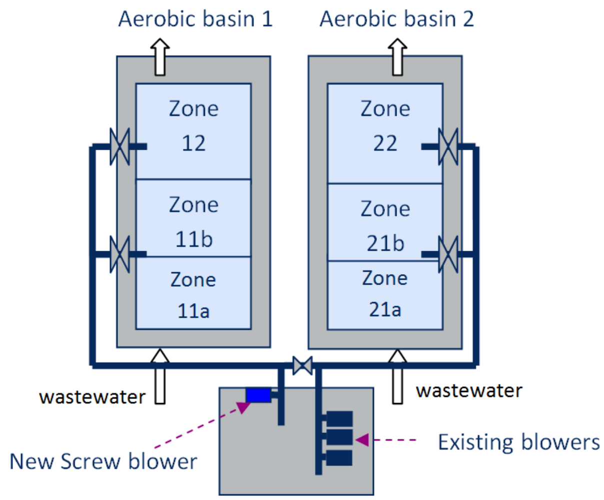

Figure 1: Aeration basins layout at the field test site.

MATERIALS AND METHODS

Compared Treatment Lines

The secondary treatment process at Sternö WWTP is divided into two identically sized separate treatment lines 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. The reference line aeration system was controlled from two DO sensors, 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 setpoints 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.

A Sanitaire advanced process control system was used to control the test line. Based on a DO sensor 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 setpoints 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 ammonium feedback control. The purpose of ammonium feedback was to keep a stable effluent ammonia concentration despite the variable influent load by adjusting the DO setpoint. Ammonium 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 2.

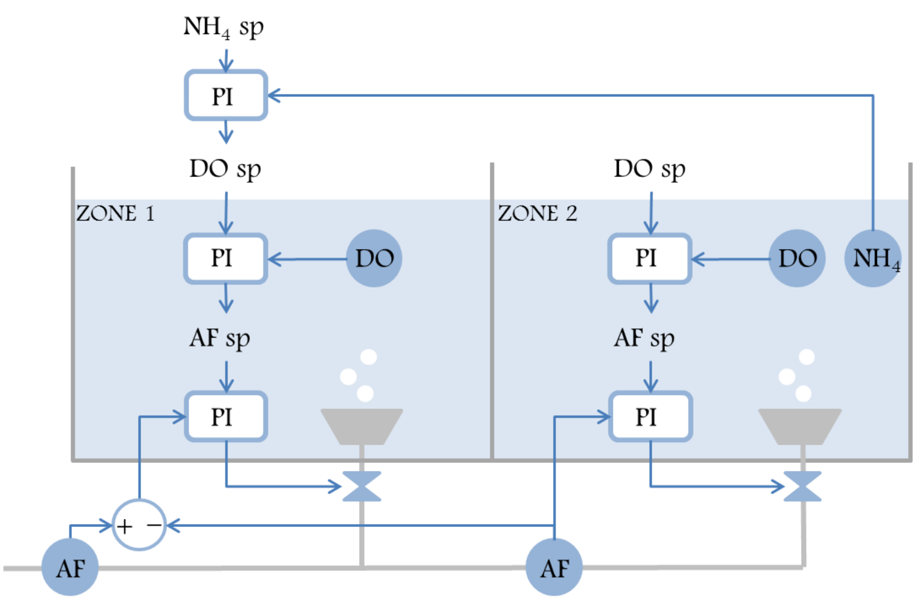

Figure 2: Sanitaire aeration control system layout implemented in the test line

The 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 setpoints 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.

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/YSI online sensors measuring DO, ammonium and nitrate according to Figure 3. Weekly composite samples for analysis of BOD_7 and NH_4-N were gathered from the inlet and the outlet to each biological treatment line (aeration basins and secondary clarifiers). The flow to each line was determined based on online 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.

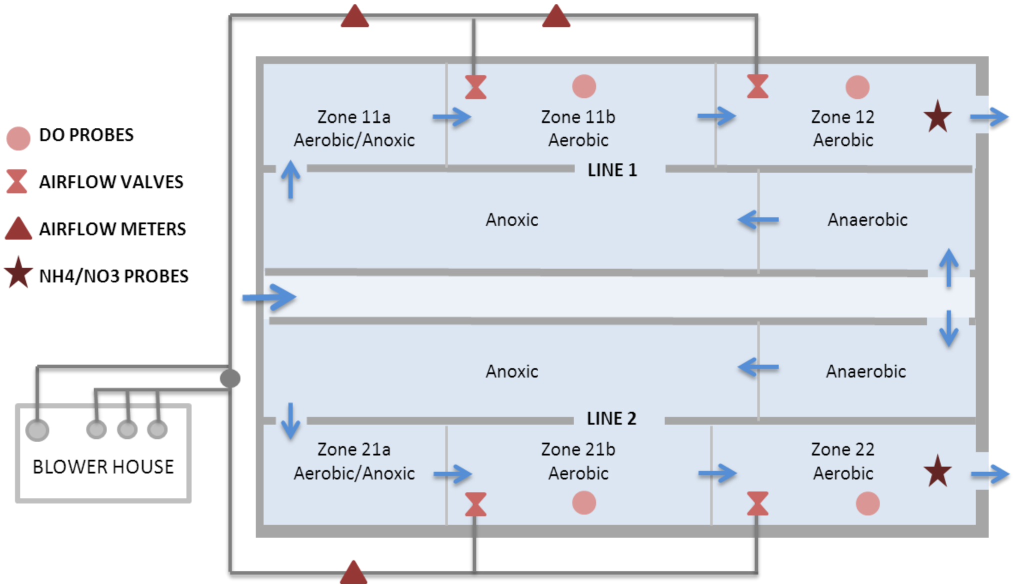

Figure 3: Process setup and on-line measurements in the test line (line 1) and the reference line (line 2)

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
$BOD_{5,r}$ = 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 O2/kWh
$AE_{f,test}$ = Test line aeration efficiency in field conditions, kg O2/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.

Calculation of Theoretical Energy Savings Based on a Set DO and Temperature

By implementing an ammonia feedback controller, the DO setpoint used in the test line was optimized for the treatment requirements. To estimate the energy savings given by this optimization compared to the fixed DO setpoint used in the reference line, a ratio between the Actual Oxygen Requirement (AOR) and Standard Oxygen Requirement (SOR) was calculated for each line. The relative difference in the ratio between the two lines is proportional to the theoretical energy savings given by the different DO setpoints used. The AOR/SOR ratio was calculated as follows:

$$\frac{AOR}{SOR} = \frac{\alpha\theta^{T-20}}{C_{sat20}} \cdot \left[C_{sat20} \cdot \beta \cdot \left(\frac{C_{surfT}}{C_{surf20}}\right) \cdot \left(\frac{P_{site}}{P_{std}}\right) - DO_{Line\ Set\ Point}\right]$$

AOR = Actual Oxygen Requirement
SOR = Standard Oxygen Requirement

$$\alpha = \frac{K \cdot L_a wastewater}{K \cdot L_a tap\ water}$$

θ = Temperature correction Factor
T= Operating temperature of wastewater, °C
C_{sat20} = The Dissolved Oxygen (DO) saturation concentration at 20°C and standard conditions, mg/l
C_{surf20} = Surface DO saturation concentration at 20°C and standard conditions, mg/l
C_{surfT} = Surface DO saturation concentration at wastewater temperature, mg/l
β = Saturation factor
P_{site} = Atmospheric pressure at the site, psia
P_{std} = Standard atmospheric pressure, psia
$DO_{Line\ Setpoint}$ = Dissolved oxygen setpoints used in zone 1 in respective line, mg/l

The factor α was assumed to 0.65 and the temperature used was 20 °C. For the site diffuser submergence, C_{sat20} was estimated to 10.3 mg/l. The following values were used for the other parameters according to standard practice: θ= 1.024, C_{surf20} = Cs_{urfT} = 9.08, β = 0.95, P_{site} = P_{std} = 14.7 psia.

RESULTS AND DISCUSSION

Energy Analysis

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 month by month data in Table 1 show that the largest energy savings were gained during February to April, which is when the water temperature was the lowest.

Table 1: Energy reduction from September 2011 to June 2012 for each month, average over the whole period

Period	Energy reduction [%]
September 2011	63
October 2011	66
November 2011	62
December 2011	68
January 2012	64
February 2012	69
March 2012	69
April 2012	64
June 2012	69
Average, whole period	66

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 setpoint. 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.

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 by 10 kPa. The pressure reduction was a result of the new aeration grid, which operated at a lower pressure and decreased the energy consumption required by the blower. 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.

Comparison of Aeration Control Strategies

Maintaining a low variation in DO values around the determined setpoint provided additional savings due to a more efficient blower operation. The difference in DO variation is illustrated in Figure 4 and 5.

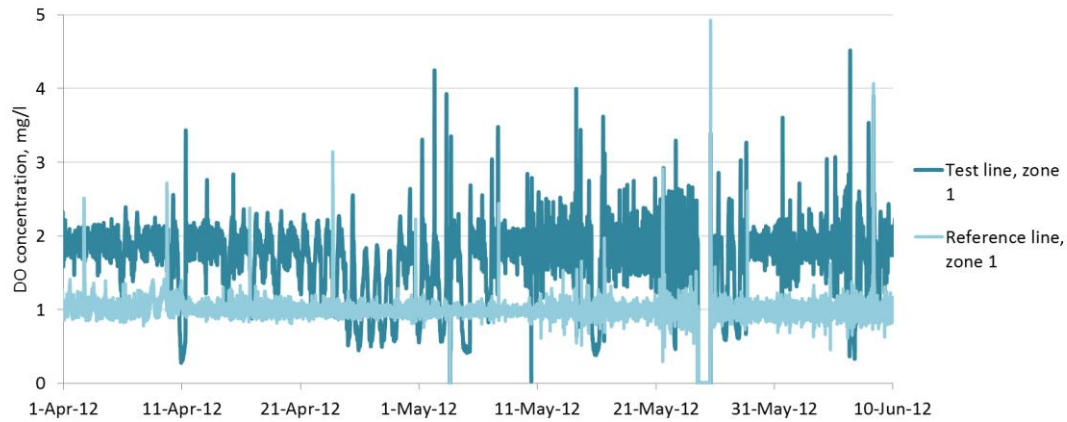

Figure 4: DO Concentration vs. time in Zone 1 for the period of April to June 2012

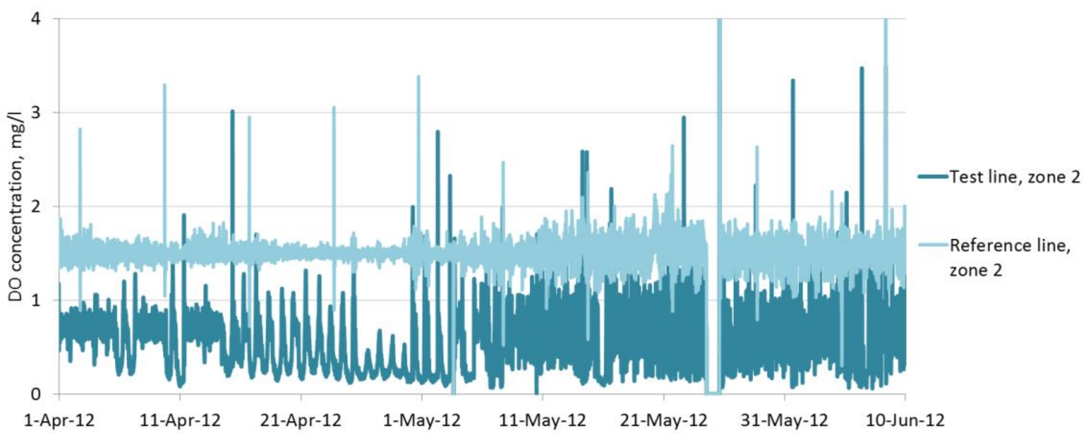

Figure 5: DO Concentration vs. time in Zone 2 for the period of April to June 2012

Figure 4 and 5 shows that the test line has less fluctuation and operates closer to the setpoint than the reference line. The tighter the DO control in a process operating system, the more energy savings will be seen. In order to compare the tightness of the two operating lines, a statistical analysis of the dissolved oxygen levels was performed for data from April to June 2012. The variance of the data, the 90% confidence interval, and the percentile breakdown were calculated. The variance of the dissolved oxygen data is a measure of the spread of the data. The differing setpoints do not play a role in this calculation. The variance both lines and zones is show in Table 3.

Table 3: Calculated variance of measured DO in both lines and zones for April to June 2012

	Variance (mg/l)
Test line, zone 1	0.032
Reference line, zone 1	0.265
Test line, zone 2	0.054
Reference line, zone 2	0.102

The 90% confidence interval means that it can be shown with 90 percent confidence that the true mean of the dissolved oxygen levels at any period of time lies within the interval shown for each line and zone. A confidence interval is based off of the sample mean for a normally distributed sample and the standard deviation. In this statistical analysis, normality was assumed because the sample size is greater than 30. The 90% confidence intervals for both lines and zones are show in Table 4. The test line has a much smaller variance in both zones which means that it has a tighter DO control.

Table 4: Calculated 90 % confidence interval of measured DO in both lines and zones for April to June 2012

	90 % Confidence interval
Test line, zone 1	(0.698, 0.702)
Reference line, zone 1	(1.694, 1.706)
Test line, zone 2	(0.997, 1.003)
Reference line, zone 2	(0.696, 0.704)

The last statistical analysis preformed was a percentile breakdown of the dissolved oxygen data for the selected time period, as can be seen in Table 5. The percentile represents a value for which the selected percent of the measured DO data is equal to or below. Concluding that overall, the test line data operate closer to their setpoint compared to the reference line for both zones 1 and 2.

Table 5: Calculated 10^{th} and 90^{th} percentile of measured DO in both lines and zones for April to June 2012

	10^{th} percentile	90^{th} percentile
Test line, zone 1	0.91	1.09
Reference line, zone 1	0.82	2.11
Test line, zone 2	1.39	1.62
Reference line, zone 2	0.19	0.94

Theoretical Energy Savings Based on DO Setpoint Values

When calculating the theoretical energy savings given by the use of different DO setpoints, the time period April to June 2012 was selected. During this period, the DO setpoint used in zone 1 in the reference line was 1.7. In the test line, the ammonia feedback controller fixed the DO setpoint to 1.0 mg/l. Table 2 summarizes the calculated AOR/SOR ratios.

Table 2: DO setpoints at calculated AOR/SOR ratio for both lines for time period April to June 2012

	DO setpoint in zone 1, mg/l	AOR/SOR ratio
Test line	1.0	0.51
Reference line	1.7	0.55

The AOR/SOR ratio is directly proportional to the oxygen required in zone 1 in each line. By assuming a linear relationship between the oxygen transferred and the airflow, as well as between the airflow and the energy consumed, the calculated AOR/SOR ratios generate a theoretical reduction in energy consumption of 8% by the use of different DO setpoints.

Treatment Performance

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, resulting in no difference between the two lines. 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.

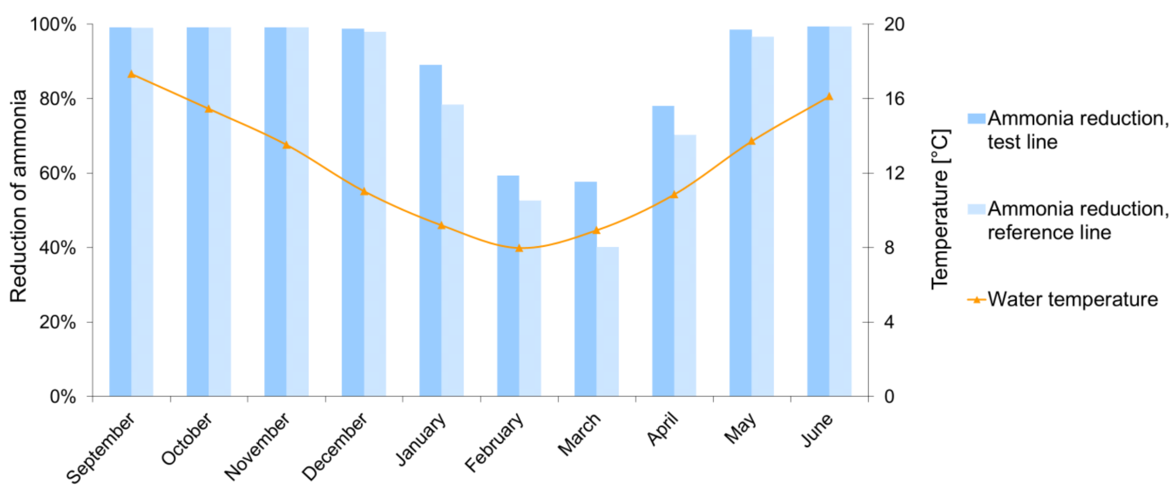

Figure 4: Ammonia reduction and water temperature for the period September 2011 to June 2012

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 setpoints of 1.7 / 0.7 mg/l in zone 1 and 2 were used in the reference line. In the test line, a fixed DO setpoint of 0.7 mg/l was used in zone 2, while the DO setpoint in zone 1 was adjusted based on the measured ammonia concentration. During a large part of the cold water period, this setpoint was set to 2.5 mg/l. The suspended solids concentration was the same in both lines.

The ammonium 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 ammonium 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. The implementation of ammonium control alone did not meet all of the process needs. However, if this control strategy was combined with a sludge age controller that takes biomass into consideration as well, there is a higher likelihood of the process controller meeting the effluent requirements, irrespective of aeration limitations. Additionally, control of aerated volume through the use of swing zones would assist with ensuring nitrification capability in colder water environments. 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.

SUMMARY

The availability of more and more advanced online instrumentation allows for automating the operation of a WWTP by automatically adapting to changing influent conditions. The use of advanced process controls to fine tune and tighten the control logic results in energy savings and process stability. By having the ability to compare parallel treatment lines, significant energy savings can be observed when implementing different aeration control strategies. The use of cascaded aeration control strategies coupled with most open valve control resulted in not only lower energy consumption, but provided an improvement in ammonia removal. The results illustrate the need for process understanding coupled with automated controls to provide even better removal of ammonia. Additionally, the comparison of two similar control strategies identified multiple areas for improvement to stabilize the process through tighter controls, and reduction in energy by optimizing the process variable setpoints.

LIST OF ACRONYMS:

AOR………………..Actual Oxygen Requirement
BOD Biochemical Oxygen Demand
DO…………………..Dissolved Oxygen
MLSS Mixed Liquor Suspended Solids
MOV……………….Most Open Valve
PE Population Equivalent
RAS Return Activated Sludge
SOR…………………Standard Oxygen Requirement
SRT Sludge Retention Time
TN Total Nitrogen
TP Total Phosphorus
VFD Variable Frequency Drive
WAS Waste Activated Sludge
WWTP…………….Waste Water Treatment Plant

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