Water Practice & Technology Vol 7 No 4
doi: 10.2166/wpt.2012.098

Energy savings potential of new aeration system: Full scale trials

A. Lazić, V. Larsson and Å. Nordenborg

Xylem, Gesällvägen 33, SE-174 87 Sundbyberg, Sweden. E-mail: aleksandra.lazic@xyleminc.com

Abstract

The objective of this work is to decrease energy consumption of the aeration system at a mid-size conventional wastewater treatment plant in the south of Sweden where aeration consumes 44% of the total energy consumption of the plant. By designing an energy optimised aeration system (with aeration grids, blowers, controlling valves) and then operating it with a new aeration control system (dissolved oxygen cascade control and most open valve logic) one can save energy. The concept has been tested in full scale by comparing two treatment lines: a reference line (consisting of old fine bubble tube diffusers, old lobe blowers, simple DO control) with a test line (consisting of new Sanitaire Silver Series Low Pressure fine bubble diffusers, a new screw blower and the Flygt aeration control system). Energy savings with the new aeration system measured as Aeration Efficiency was 65%. Furthermore, 13% of the total energy consumption of the whole plant, or 21 000 €/year, could be saved when the tested line was operated with the new aeration system.

Key words: aeration system, DO cascade control, energy savings, fine bubble diffusers

INTRODUCTION

The conventional activated sludge process with nitrification and denitrification is a commonly used wastewater treatment technology for removal of both organic material (measured as BOD) and nitrogen (present in the form of ammonium). The first step in nitrogen removal, nitrification, is a highly energy consuming step due to the need for aeration. 4.6 mg of oxygen is needed to oxidise 1 mg of ammonium, and 1.2 mg of oxygen is needed to oxidise 1 mg of BOD. Blowers that are providing air to diffusers need to work against high pressure in the air mains (due to static water pressure above diffusers, pressure losses over the membranes and pressure losses in pipes and valves) and need to maintain the desired pressure in the common manifold. A higher required pressure for the blower leads to an increase in consumed energy. Therefore, aeration stands for the largest portion of the total energy consumption at plants with nitrogen removal.

According to Olsson (2008) and Ingildsen (2002), the biological-secondary treatment is the most energy demanding treatment step in the whole wastewater treatment plant (WWTP). The main reason for this is aeration, which depending on the size of the plant can consume between 50 and 80% of the plant's total energy consumption.

Energy costs in the wastewater industry are rising (EPA 2010). With an increased energy price more and more treatment plants, both public and private owned, are looking into decreasing their energy consumption and therefore lowering their energy costs. At the same time many WWTPs are facing more stringent effluent requirements which require more air but also better optimised processes. Therefore, an energy efficient aeration system is becoming a frequently used term as a goal for WWTPs. By using an aeration control system, one can achieve the same or even better treatment and at the same time save energy.

In literature, a wide range of complexity for aeration control systems is presented, spreading from simple on/off control (Traoré *et al*. 2005) to advanced model predictive control (MPC) (Holenda

doi: 10.2166/wpt.2012.098

et al. 2007). Full scale testing is not very common in the literature and most strategies are evaluated through simulations. In general, a large part of the aeration control studies made today include some kind of feedback or feed forward effluent control, often compared with a simple fixed dissolved oxygen (DO) set point algorithm. Advantages of using feedback or feed forward effluent control are many, including potential energy savings and tracking of the effluent concentrations. However, these control algorithms also include an increased probe uncertainty, lag times as well as extra costs (Nordenborg 2011).

While the strategies presented in literature tend to be more and more advanced, the control used at WWTPs today are still relatively simple. In a status report of large WWTPs in Europe made 10 years ago (Jeppson *et al.* 2002) feedback or feed forward effluent control is stated to be seldom used and the most common control strategies are said to be different types of PID controllers.

The objective of this work is to decrease energy consumption of the aeration system at one WWTP in the south of Sweden where aeration stands for 44% of the total energy consumes. This was done by combining the knowledge of how to design an energy efficient fine bubble aeration system with how to operate it with a new aeration control system.

Flygt aeration control system

Flygt Aeration Control System (ACS) is a Xylem developed software for advanced monitoring and control (M&C) of the aeration process within secondary treatment. The control philosophy is to maximize overall energy efficiency and maintain the desired level of DO in aerated basins, as well as to preserve good treatment. The M&C system is based on DO cascade control with two PI controllers for each control (throttling) valve. The DO cascade control consists of an inner control loop, which controls the airflow, and an outer control loop which controls the DO concentration.

Furthermore, the Flygt ACS is equipped with most open valve logic (MOVL) that decreases pressure losses in the system by keeping the valves as open as possible (up to desired 95%). Based on the status of the valves, the MOVL calculates manifold pressure set points (low, average and high) for blower control. With this it is possible to run blowers at a lower air pressure and therefore save energy.

In addition, the Flygt aeration control is also equipped with fouling preventive control called *air bumping* or simply *cleaning*, where high airflow is induced for 5 min once per week in order to stretch the membrane and break the built biofilm.

Field test site

The treatment plant was built in 1997 and is dimensioned for 26,000 population equivalents (PE). In 2010 only 17 800 PE were connected (calculated from the current load as 70 g BOD/p/d). Effluent requirements are 10 mg/l BOD and 0.5 mg/l tot-P as monthly average, and 12 mg/l tot-N as yearly average. It 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.

Fine bubble tube diffusers were operating since 1997 in both lines, designed with constant diffuser density (without tapering). The first line was used as a *test line* for implementation of the Flygt ACS with new Sanitaire Silver Series Low Pressure fine bubble diffusers (with roughly the same diffuser density as in the reference line) and a new screw type blower. The second line is used as a *reference line*, running with a current control system with simple DO control (a DO controller determines the

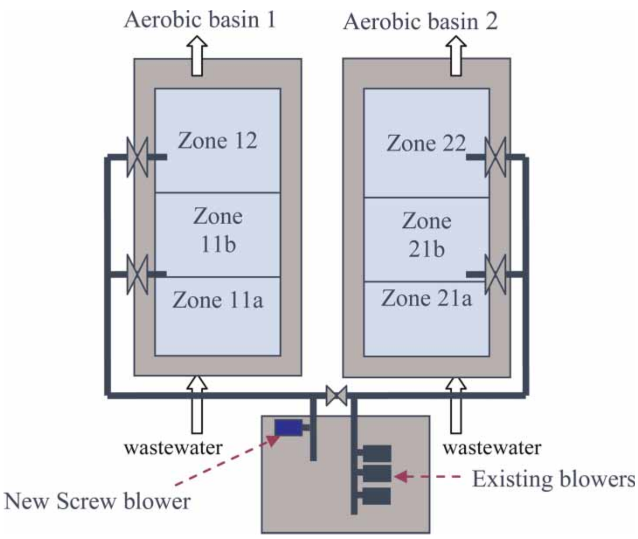

Figure 1 | Aeration basins layout at the field test site.

valve opening directly from the DO measurement without an inner control loop), old fine bubble tube diffusers and three old lobe blowers.

In both lines, the first two aerobic zones (later called zone 1) were controlled with one control butterfly valve and one actuator. The last aerobic zone (later called zone 2) has its own control valve with actuator (see Figure 1). DO set points were 1.7 mg/l for the zone 1, and 0.7 mg/l for the zone 2. A lower set point in the last zone was chosen as water is recycled after aeration to anoxic zones for denitrification, where high DO would disturb the process (see also Figure 2). The swing zones (both 11a and 21a) were used as aerobic zones if not stated differently.

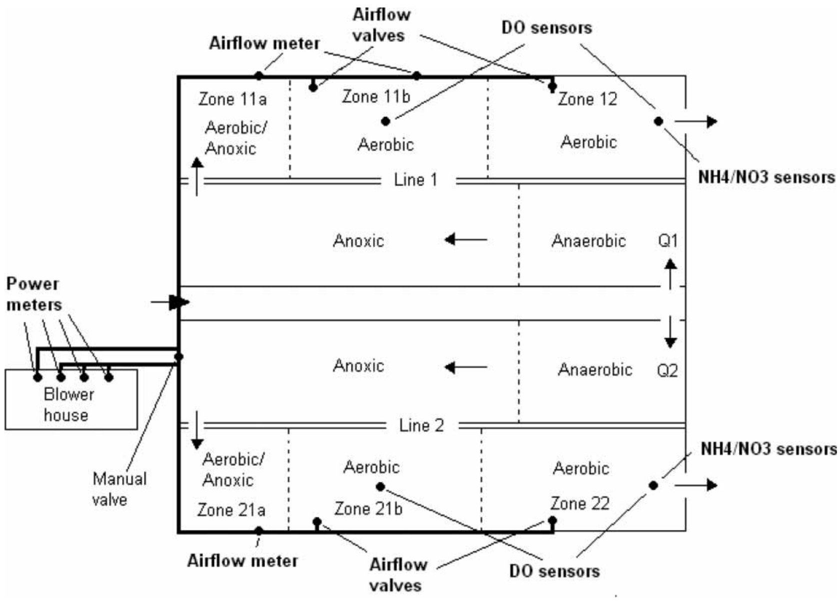

Figure 2 | Position of on-line measurements in the biological treatment step at the test plant (Larsson 2011).

MATERIAL AND METHODS

The implementation of new equipment and the new control system in the test line was made in several steps. Based on these installations there are three evaluation periods, as can be seen in Table 1. In

doi: 10.2166/wpt.2012.098

Table 1 | Evaluation periods with new aeration equipment in the test line

Evaluation period	Time period 2011	New aeration equipment
1	April 6 – April 20	New screw type blower with VSD Flygt ACS DO cascade control –not tuned
2	July 6 – Sept. 7	Sanitaire SS II LP
3	Sept 7 – Nov. 16	Flygt ACS DO cascade control- fine tuned DO profile adjusted MOVL – fine-tuned

April 2011, a new blower and a DO cascade control were implemented in the test line. This DO cascade control was not tuned in April but rather adjusted with the same controller parameters as in the reference line. Necessary equipment for measuring the airflow, DO and ammonium concentrations (WTW sensors) was installed in both lines in April.

There was a long break between evaluation periods 1 and 2. This was caused by a long installation time for the new diffusers, which involved emptying the basin, installing the diffusers and also repairing baffle walls between the aeration zones. During periods 2 and 3 aeration in the swing zones in both lines was turned off and zones were used as extended anoxic zones. In September 2011, the Flygt DO control was fine tuned together with the MOVL. The MOVL was adjusted to operate the air pressure so that the valves were 70 to 95% open (of their controllable range). In addition, the DO profile (set points) was changed to 0.7 mg DO/l in zone 1 and 1.0 mg DO/l in zone 2, as discussed later.

In both treatment lines (the test line and reference line) water quality measurements were made on-line, as shown in Figure 2. On a weekly basis samples for BOD_7 and NH_4^+-N concentrations were taken in the inlet to each line and in the outlet from the secondary sedimentation basins.

In addition, measurements and calculations of the inflow distribution to the two treatment lines have been performed. It was found that the flow fraction to the reference line and test line is 53% and 47% respectively.

Oxygen transfer calculations

In order to evaluate energy savings potential in terms of aeration efficiency (AE) several calculations were performed as shown in Table 2.

Economic analysis- LCC

The weekly economical savings were calculated based on the weekly energy savings in (1):

$$€_{\text{weekly savings}} = \text{energy price} \bullet E_{\text{weekly savings}} \tag{1}$$

where,

$€_{\text{weekly savings}}$ = economical savings per week [€/week]
Energy price = energy price for the plant [€/kWh]
$E_{\text{weekly savings}}$ = energy savings per week [kWh/week]

Furthermore the economical evaluation also considers the return period. In order to calculate the return period the annual savings first need to be calculated, as shown in (2):

$$\text{Annual savings} = \text{Energy consumption} \bullet \frac{\text{Energy savings}}{100} \bullet \text{Energy price} \tag{2}$$

doi: 10.2166/wpt.2012.098

Table 2 | Calculations of oxygen / aeration parameters (modified from ACSE-18–96 1996)

Parameter definition	Unit	Formula / value
OTR_{fi} -Oxygen Transfer Rate in field conditions	kg/day	$OTR_{fi} = [X \cdot BOD_{5,r} + Y \cdot NH_4\text{-}N_r] \cdot [\beta \cdot C^*_\infty / (\beta \cdot C^*_\infty - DO_{fi})] + Q \cdot DO_{fi}$
where: X = oxidation coefficient for BOD_5	kg O_2/kg BOD_5	1.2 (EPA 1989)
Y = oxidation coefficient for NH_4	kg O_2/kg NH_4	4.57 (Metcalf & Eddy 2003)
$BOD_{5,r}$ = removal of oxygen demand	kg/day	$BOD_5 = BOD_7/1.15$ (Norrström 1976)
$NH_4\text{-}N_{,r}$ = removal of ammonium	kg/day	
β = process water C^*_∞ / clean water C^*_∞		0.95 (ACSE-18-96 1996)
C^*_∞ = DO saturation concentration at T	mg/l	
DO_{fi} = DO in field conditions	mg/l	
Q = the flow through the line	m^3/day	$= Q_{tot} \cdot$ Flow fraction
Denitrification credit = 0		
AE_{fi} – Aeration Efficiency in field conditions	kg O_2/kwh	$AE_{fi} = OTR_{fi} / PWR_{fi}$
PWR_{fi} = power consumed	kwh/day	

where,

Energy consumption = total energy consumption for the plant [kWh/ year]
Energy savings = total energy savings for the plant due to improved aeration [%]
Energy price = energy price for the plant [€ /kWh]

The average energy price for the period January 2011 to October 2011 (1.120 SEK/kWh = 0.12 €/kWh) was used for the energy price. This period was used since it is a recent time period and includes the energy price difference of winter and summer.

$$\text{Return period} = \frac{\text{Total price}}{\text{Annual savings}} \tag{3}$$

where,

Return period = time it takes before the investment is retuned [year]
Total price = total price of the investment [€]
Annual savings = savings per year [€ /year]

The total price of the investment includes direct capital expenses (CAPEX) for blower, diffusers, on-line measurements, equipment and control system, as well as installation costs. Operational expenses (OPEX) were not included in this study.

Control strategy and Tuning

In Figure 3, a visualisation of the overall control strategy in the test line is shown. Two butterfly control valves were used, each controlled with a DO cascade loop with two PI controllers (DO and air flow). When using non-linear valves, such as butterfly valves, together with DO cascade control, the non-linear characteristic of the valve is counteracted. This is possible since the control is made in two steps where the airflow controller keeps track of the airflow, while the DO controller keeps track of DO. DO cascade control also corrects for disturbances faster than simple DO control, since the two controllers can work more stable when the additional measurement of airflow is included compared to the simple DO control.

The performance of a PI controller is highly dependent on the tuning of the controller gain and integral time. Fine tuning of PI cascade controllers was performed at the plant using the Lambda tuning method described by Carlsson & Hallin (2010). Parameters for the DO controller and the air flow controller are given in Table 3.

doi: 10.2166/wpt.2012.098

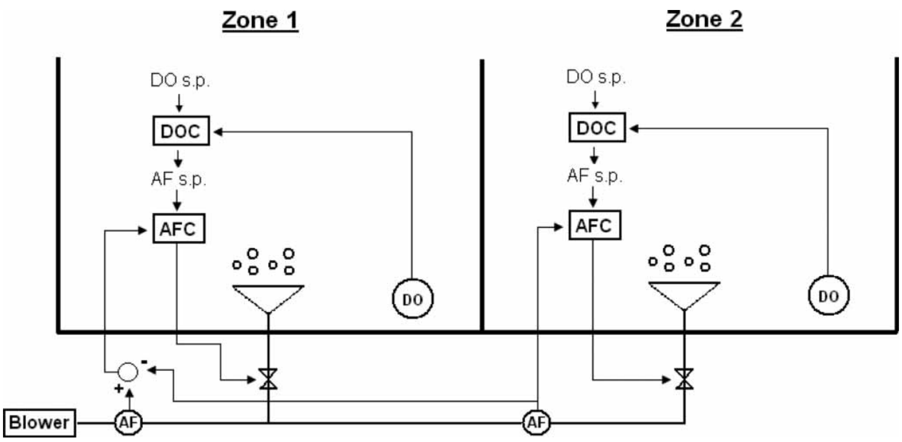

Figure 3 | Visualisation of the overall control of the test line. DOC is the DO PI-controller and AFC is the airflow PI-controller. The circles with DO and AF represent online measurements of DO and airflow (modified from Larsson 2011).

Table 3 | Parameters of PI controllers for a test line consisting of zone 1 (two aeration grids) and zone 2 (one aeration grid)

	Zone 1 = Grid 1 and Grid 2		Zone 2 = Grid 3	
Parameters:	**DO controller**	**Air flow controller**	**DO controller**	**Air flow controller**
K	0.57	0.45	0.62	0.50
T_i (sec)	335	17	270	13

Where K = proportional gain; T_i = integral time.

RESULTS AND DISCUSSION

Comparisons of the aeration and control systems in the test and reference line in terms of aeration efficiency in field conditions, airflow and energy savings are presented in Table 4. In this table an average value is given for each period. The results for period 1 are based on 2 weeks of data, for period 2 on 8 weeks of data and for period 3 on 10 weeks of data.

Table 4 | Summary of results from the three periods: P1 = new blower and new DO control system was in place, P2 = P1 + new diffusers, P3 = P2 + fine tuning of controllers, new DO profile and MOVL

	AE_{fi} [kg O_2/kWh]		Airflow savings	Energy save	Energy save	Actual save L1
Evaluation period 2011	**Test Line**	**Ref.Line**	**[%]**	**[%]**	**[kWh/week]**	**[€/week]**
P1 (April)	2.1	1.4		34	1,565	184
P2 (July-Aug)	1.9	0.8	20	57	4,302	506
P3 (Sept-Nov)	2.2	0.8	30	65	3,989	469

During period 1, the test line consumed 34% less energy than the reference line. This evaluation period contains the new blower and the new DO cascade control with a DO profile of 1.7 mg/l for zone 1 and 0.7 mg/l for zone 2. Most of the energy savings comes from exchanging the blower.

The second evaluation period involved new Sanitaire diffusers which were installed between periods 1 and 2. After changing diffusers in the test line the pressure in the aeration system decreased by 10 kPa and was ranging between 57 and 60 kPa during periods 2 and 3. The pressure in the reference line was 70 kPa during all periods. Lower operating pressure in the test line decreased energy consumption of the blower for the same air flow.

doi: 10.2166/wpt.2012.098

During this period, the energy savings increased from 34% up to 57%. This additional 23 percentage points of the saved energy for the period 2 was accomplished by a higher oxygen transfer efficiency of new diffusers and lower pressure losses compared to the tube aeration system in the reference line.

Since the plant is under loaded and the temperature of the water during summer was high which promoted nitrification process, more efficient diffusers created problems to keep the DO concentration in the last zone at 0.7 mg/l that could influence the denitrification process negatively. In this zone air flow was already at the lowest allowed level determined by the mixing criteria. In this period (period 2) the swing zone was used as an anoxic zone.

The third evaluation period involved fine-tuning of the DO cascade control, a new DO profile and activation of the MOVL. During this period the DO profile (DO set-point in zone 1/zone 2) in the test line was changed from 1.7/0.7 to 0.7/1.0 mg/l due to the problems with too high DO concentration (above 1.8 mg/l) in the last zone (zone 2). The idea was to decrease the oxidation of organic constituents and ammonium in zone 1 and therefore save some load to zone 2 in order to distribute the removal process more evenly over the total aeration volume, thus using the aeration capacity in a more energy efficient way.

After the fine tuning of DO controllers and finding a proper DO profile totally 65% of energy was saved in the period 3 (Table 4). This additional 8 percentage points of savings comes also from the implementation of MOVL, which allowed the blower to work at a lower air pressure and valves were being operated to be open at least 70%, which decreased pressure losses over the valves.

The total energy savings of 65% corresponds to an airflow reduction of 30% with equally efficient treatment efficiency in both lines.

Comparing periods 2 and 3 it can be seen that the highest weekly energy savings as kWh/week were accomplished during the evaluation period 2 due a couple of peak load weeks. During this period (July – August 2011) ammonium load decreased due to summer fluctuations but BOD load was equally high as in April 2011 due to problems with primary sedimentation.

Despite the low oxygen level in the test line, settling properties of the sludge were kept in the same level as in the reference line. During the whole testing period filamentous bacteria were not found in the sludge and sludge settled very well.

One of the main goals for implementing the aeration control system was to decrease energy consumption and in the same time preserve the treatment efficiency. The reduction of BOD_7 and NH_4 for the three evaluation periods is shown in Table 5. It can be seen that the BOD_7 removal efficiency is almost the same (96 to 97%) for both treatment lines for all periods. The NH_4 reduction was very good in both treatment lines (99%) for the evaluation periods 2 and 3. During the first evaluation period, that has only two weeks of data, the NH_4 reduction was lower comparing to other periods (71% in the test line and 88% in the reference line).

Table 5 | Average reduction of BOD_7 and NH_4.

	Influent BOD_7 [mg/l]		Effluent BOD_7 [mg/l]		Influent NH_4 [mg/l]		Effluent NH_4 [mg/l]	
Period	**Test Line**	**Ref Line**	**Test Line**	**Ref Line**	**Test Line**	**Ref Line**	**Test Line**	**Ref Line**
P1	100.0	134.8	3.9	4.0	20.0	16.5	5.9	2.3
P2	104.3	104.0	3.0	3.0	12.5	12.7	0.1	0.1
P3	78.3	79.0	2.9	2.7	11.9	12.2	0.1	0.1

The total energy savings of 65% achieved in this study is a combination of different contributions: new aeration equipment (23 percentage points), new blower (34 percentage points), new Flygt aeration control system (8 percentage points), new and reliable online instrumentation, but also combining the equipment with the knowledge of how to operate and optimise the process.

It has been reported in the literature that the implementation of the aeration control in certain WWTPs has attained energy savings of 10–20% (Carlsson & Hallin 2010). Åfeldt (2011) tested zone-individual DO cascade control and compared it with the old aeration control (DO cascade control where the airflow was evenly spread out to all aerated zones). Results from this study showed that energy consumption could be decreased with 10% with the zone-individual DO cascade control compared to the old aeration control.

The energy consumption per quantity of treated water for the tested plant was 0.1 kwh/m^3 as an average for all three periods. The energy consumption per nutrient mass was 7.9 kwh/kg NH_4 removed and 1.1 kwh/kg BOD removed. According to the literature (Kjellén and Andersson 2002) energy consumption of the aeration step within the secondary treatment for the 100 000 PE WWTP is reported to be 0.153 kwh/m^3 of treated wastewater. Lingsten *et al*. (2011) conducted a mapping of energy use of Swedish water and wastewater plants in 2008. It was shown that bigger plants (>10,000 PE) are more energy efficient per m^3 of treated water than smaller plants (<10,000 PE).

By changing the aeration system in the test line the total energy consumption of the plant decreased with 13% (see in the Figure 4). With this energy saving for the whole plant, around 21,000 € could be saved per year. That leads to a payback time of 4.5 years. The payback time can also be calculated for the different equipment by comparing investment and installation costs with the percentage of energy savings per chosen equipment. The shortest time was found for the new diffusers, which had a payback time of only 1.5 years. In addition, if both lines were upgraded, the payback time would be 3.3 years (based on projections of how much energy could be saved). The total price of upgrading both treatment lines is not the double price for upgrading only one treatment line since some equipment, for example control system, can be used for both treatment lines.

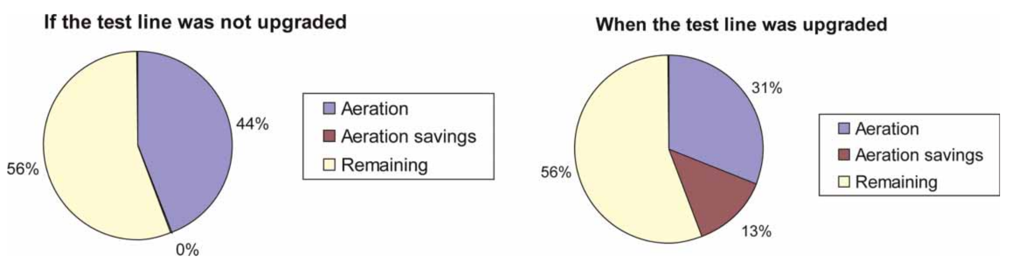

Figure 4 | Total energy consumption of the tested plant: before and after upgrade (Larsson 2011).

The future work will focus on improving the energy efficiency further by implementing an ammonium feedback control loop in the test line as well as upgrading the reference line with new Sanitaire Silver Series fine bubble diffusers with new tapered design.

CONCLUSIONS

Comparisons of two different aeration and control systems in terms of aeration efficiency, airflow and energy savings are presented. Full scale trials showed that the energy consumption for the aeration could be reduced by 34% by exchanging blower from lobe to screw type, and M&C system from simple DO control to Flygt cascade DO control. The energy consumption could be reduced by additional 23 percentage points by changing diffusers from old tube diffusers to Sanitaire Silver Series II LP in the test line. After fine tuning of DO controllers, finding a proper DO profile (set points for zone 1/zone 2 were set to 0.7/1.0 mg/l) and implementing most open valve logic, a total energy reduction of 65% was achieved. The energy savings corresponds to an airflow reduction of 30% with equally efficient treatment (97% of BOD reduction and 99% of NH_4 reduction).

doi: 10.2166/wpt.2012.098

The total energy savings of 65% achieved in this full scale study is a combination of different contributions: new aeration equipment (23 percentage points), new blower (34 percentage points), new Flygt aeration control system (8 percentage points), new and reliable online instrumentation, but also combining the equipment with the knowledge of how to operate and optimise the process.

The payback period for the implemented aeration system (based on capital costs) was calculated to 4.5 years. The energy savings of the new aeration equipment decreased the total energy consumption of the whole plant with 13% which corresponds to annual savings of 21,000 €. If both lines were upgraded with the new aeration system the payback period would decrease to 3.3 years with annual savings of 46 000 €.

ACKNOWLEDGEMENTS

Authors would like to thank the personal from the tested WWTP (Ida Schyberg, Per Karlsson and Stefan Lennartsson) for their support and cooperation. Authors are also grateful to Dan Fujii, an application engineer from Xylem, for his valuable comments.

REFERENCES

ACSE-18–96 1996 *Standard Guidelines for In-Process Oxygen Transfer Testing*.

Åfeldt, E. 2011 Evaluation and improvement of oxygen control at Himmerfjärden wastewater treatment plant. (In Swedish) Master thesis, Royal Institute of Technology, Stockholm, Sweden.

Carlsson, B. & Hallin, S. 2010 Applied Automatic control and microbiology of municipal wastewater treatment plants. (In Swedish) Svenskt Vatten Utveckling, Publikation U10.

EPA 1989 Design Manual, Fine Pore Aeration Systems. U.S. Environmental Protection Agency. EPA/625/1-89/023.

EPA 2010 Evaluation of Energy Conservation Measures for Wastewater Treatment Facilities. U.S. Environmental Protection Agency. EPA 832-R10-005.

Holenda, B., Domokos, E., Rédey, Á. & Faxakas, J. 2007 Dissolved oxygen contriol of the activated sludge wastewater treatment process using model predictive control. *Computers & Chemical Engineering* **32** (6), 1270–1278.

Ingildsen, P. 2002 Realising full-scale control in wastewater treatment systems using in situ nutrient sensors. PhD thesis, Dept. of Ind. Electrical Engineering and Automation (IEA), Lund University, Lund, Sweden.

Jeppson, U., Alex, J., Pons, M. N., Spanjers, H. & Vanrolleghem, P. A. 2002 Status and future trends of ICA in wastewater treatment – a European perspective. *Water Science and Technology*, **45** (4–5), 485–494.

Kjellén and Andersson 2002 Energy handbook for wastewater treatment plants. (In Swedish) Svenskt Vatten Utveckling, Rapport Nr 2002–02.

Larsson, V. 2011 Energy savings with a new aeration and control system in a mid-size Swedish wastewater treatment plant. Master thesis Aquatic and Environmental Engineering - UPTEC W11 034, Dept. of Information Technology, Uppsala Univ., Uppsala, Sweden.

Lingsten, A., Lundkvist, M., Hellström, D. & Balmér, P. 2011 Swedish water and wastewater utilities use of energy in 2008. (In Swedish) Svenskt Vatten Utveckling, Rapport Nr 2011–04.

Metcalf & Eddy 2003 *Wastewater Engineering – Treatment and Reuse*. 4th edn. McGraw-Hill Higher Education.

Nordenborg, Å. 2011 Studies regarding dissolved oxygen control – a review. Internal report, Xylem Inc.

Norrström, H. 1976 'Chemical pulping'. *Pure and Applied Chemistry (Great Britain)*. **45**, 181–186.

Olsson, G. 2008 More Effective Water Sewage Plants. (In Swedish) Svenskt Vatten Utveckling, Rapport Nr 2008-19.

Traoré, A., Grieu, S., Puig, S., Corominas, L., Thiery, F., Polit, M. & Colprim, J. 2005 Fuzzy control of dissoled oxygen in a sequencing batch reactor pilot plant. *Chemical Engineering Journal*, **111** (1), 13–19.