Energy optimization of the aeration process at Käppala wastewater treatment plant

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Abstract In conventional wastewater treatment plants the aeration of the biological treatment process is often one of the largest energy consumers. As a part of making Käppala wastewater treatment plant (WWTP) in Stockholm Sweden more energy efficient a full-scale optimization experiment of the dissolved oxygen (DO) control in the aerobic tanks have been performed. In the strategy tested, each aerated zone was separately controlled and the spatial DO profile changed into a structure that avoids unnecessarily high DO levels. By using ammonium- and DO- feedback controllers the strategy became more sensitive to changes of influent load. The strategy gave a reduction of the total airflow of 18% and with preserved treatment efficiency. A modified version of this strategy have then been implemented to the plant as the conventional DO control system and the results are similar to those in the preceding experiments.

Key words aeration; ammonium- feedback; DO- feedback; Ki,a-function

INTRODUCTION

A mapping of the energy consumption at the Käppala WWTP revealed that the aeration of the biological treatment process corresponds to approximately 20% of the electrical consumption at the plant. Variations of influent load over the year in combination with discharge limits for low effluent ammonium concentrations give rise to inefficient aeration of the aerobic tanks and situations where the aerated volume has greater than needed capacity. The problem is well known (Sahlmann et al., 2004; Ekman et al., 2006; Vrecko et al., 2006) and a cause of unnecessary costs in many plants. By improving the DO control so that the spatial DO profile is smooth and by using supervisory control from the treatment result (e.g. effluent ammonium) energy can be saved without deteriorating effluent quality.

See also Ingildsen (2002), Olsson et al. (2005) and Ayesa et al. (2006) for other full scale implementations and Olsson and Andrews (1978) for some pioneering work.

Käppala WWTP

The Käppala WWTP is situated northeast of Stockholm, the capital of Sweden, and receives sewage from eleven municipalities north and northeast of Stockholm. Between the years 1994 and 2000 the plant was rebuilt and expanded with five new lines. The old part of the plant consists of six lines but it only receives one third of the incoming flow since the new part is twice the size in volume. The capacity of the plant is 700 000 p. e. and the current load is 530 000 p. e. The process layout of the plant is described in Figure 1. The biological treatment is an activated sludge process with UCT-configuration. The nitrogen removal is carried out in a pre-denitrification process without any addition of external carbon. The phosphorous removal comprises of biological phosphorous removal in the old part of the plant and of simultaneous precipitation in the return sludge flow in the new part of the plant.
Aeration in the biological treatment process

The number of aerated zones in each aerobic tank in the biological treatment lines varies between four and six. The first aerated zone is equipped with agitators and can be switched to an anoxic zone if needed. The aeration is performed with fine bubble diffusers (Sanitaire) placed on the bottom of the tanks. The lowest allowed airflow for each diffuser in the zones without agitators is 0.75 Nm$^3$/h in the old part of the plant and 1.2 Nm$^3$/h in the new part to prevent sedimentation of the sludge. The number of diffusers per zone decreases for each following zone as the BOD and ammonium load decreases. The oxygen transfer efficiency is higher in the new part of the plant compared to the old part due to deeper tanks (10 and 6 meters respectively) and focus of the experiment has been on the old part.

DO control system

The original DO control strategy is based on a linear air flow distribution designed to gradually decrease the air flow to the aerated zones according to a step like structure. Two DO probes, one situated in the first zone and one in the last, controls the airflows. The first probe controls the total airflow to the aerobic tank. The second one controls the inclination of the step like structure. When the DO concentration in the last zone deviates from its DO set point, the inclination is shifted, affecting the DO concentration in the first zone. This causes the DO probe in the first zone to change the total airflow to the aerobic tank. The strategy is illustrated during low and high loading conditions in Figure 2. There are four zones in the illustration but the principle is the same also in tanks with five or six zones.

Figure 1 Process layout of Käppala WWTP.

Figure 2 Air flow profile during low and high load (modified from Borglund, 2005).
This strategy runs well from a nitrogen removal standpoint. The degree of nitrogen removal is normally 80%. But during low loading conditions and high influent temperatures, when the nitrification rate is high, situations occur when the majority of the ammonium and organic carbon is removed in the first few zones. The air flow in the last aerated zone will then be kept at the lowest allowed level but intermediate zones are restricted by the imposed air flow profile given in Figure 2. This leads to elevated DO concentrations in the last aerated zone and unwanted stabilization of the sludge, which may inhibit the denitrification processes in the anoxic zones. This is a highly inefficient utilization of the aerated volumes resulting in unnecessarily high energy consumption.

**METHODS**

**Oxygen transfer**

The rate at which oxygen is transferred to water is affected by the $K_{La}$-function. The relationship between the $K_{La}$-function and airflow rate can be expected to be nonlinear. A typical model is given by (Lindberg, 1997):

$$K_{La}(q_{air}) = k_1(1 - e^{-k_2 q_{air}})$$

where

$q_{air} = \text{airflow rate (m}^3/\text{h)}$

$k_1 = \text{constant (1/h)}$

$k_2 = \text{constant (h/m}^3\text{)}$

A change in airflow affects the DO concentration according to (Olsson and Newell, 1999):

$$\frac{d(\text{DO}(t))}{dt} = K_{La}(q_{air}(t)) \cdot [\text{DO}_{sat} - \text{DO}(t)] + \frac{Q}{V} [\text{DO}_m(t) - \text{DO}(t)] - R(t)$$

where

$K_{La}(q_{air}(t)) = \text{oxygen transfer rate as a function of airflow (l/h)}$

$\text{DO}_{sat} = \text{DO saturation level (mg/l)}$

$\text{DO}(t) = \text{DO concentration (mg/l)}$

$\text{DO}_m(t) = \text{DO concentration of incoming water (mg/l)}$

$R(t) = \text{oxygen consumption rate due to microbial activity (mg/l-h)}$

$Q(t) = \text{incoming flow (m}^3/\text{h)}$

$V = \text{aerated volume (m}^3\text{)}$

$q_{air}(t) = \text{airflow (Nm}^3/\text{h)}$

From (2) it can be seen that the driving force for mass transfer of oxygen is lower at DO concentrations close to the level of oxygen saturation. Since high airflows leads to high DO concentrations, and because of the nonlinear structure of the $K_{La}$-function, high airflows give an inefficient oxygen transfer. The original DO control strategy at Käppala WWTP (Figure 2) is based on a linear air flow distribution with high airflows in the first aerated zones and low air flows in later zones. The amount of oxygen transferred per added volume of air is much lower in the first zones compared to later zones. This is not advantageous from an energy point of view.

**Growth rate of nitrifying bacteria**

The rate at which growth and decay of bacteria occurs is a key parameter for a successful biological treatment (Poduska and Stenstrom, 1980). The growth rate of nitrifying microorganisms depends on several factors where the DO and ammonium concentrations are the most important ones. The
growth rate is commonly expressed according to Monod kinetics (Henze et al., 1987). The gradient of the growth rate decreases as the concentration increases. Due to this behavior there is a potential to decrease high DO concentrations in an aerated zone with only a minor decrease of the growth rate of the nitrifying bacteria. Similarly, there is a potential to increase the growth rate substantially by increasing the ammonium concentration in an aerated zone where it is low.

In summary it can be concluded that both due to the nonlinear oxygen transfer dynamics and the growth rate function there is a potential for energy savings by an optimal use of the spatial DO profile (i.e. to avoid zones with unnecessarily high DO levels and to avoid low ammonium concentrations in intermediate zones).

The new DO control strategy - Separately controlled zones with ammonium- and DO-feedback
The new strategy was tested in full scale in one of the lines in the biological treatment in the old part of the plant. Sampling of influent and effluent load in experimental and reference line was carried out during the full length of the trials and measured airflows were normalized to any differences in load. The strategy is illustrated in Figure 3. By installing additional DO probes in the experimental line, the airflow to each aerated zone was controlled with its own DO set point through a cascade control strategy (Olsson and Newell, 1999). Here, a secondary slave controller is used to control the airflow to each zone. The output from a master controller functions as the set point for the secondary controller. This decrease negative effects of nonlinear characteristics of the air valves and gives a quick reaction on flow disturbances. With the new strategy each aerated zone is independent of surrounding zones, and guarantees that no zone will use higher airflows than needed for the instantaneous oxygen requirements. When the influent load decreases, zone 2 and 3 are no longer restricted by the imposed air flow profile (Figure 2) and will be able to lower the airflow sufficiently to prevent elevated DO concentrations in the last aerated zone and give energy savings.

By using the same DO set points to the master controllers in the cascade control in zone 1, 2 and 3, the high airflows normally used in zone 1 and 2 can be reduced and compensated by a smaller increase of the airflow in zone 3 because of the higher driving force of mass transfer at lower DO concentrations and the dynamics of the growth rate function of the nitrifying bacteria. The net effect is that the same amount of oxygen is transferred and the same amount of ammonium removed but with a lower air consumption. This gives an additional energy saving during normal or high loading conditions.

The DO set points to the master controllers in the cascade control were controlled with two supervisory feedback controllers. By using an ammonium- feedback controlling the DO set points in zone 1, 2 and 3 with online measurements in effluent, the DO set points will adapt to the current load, see also Lindberg and Carlsson (1996). However, since changes in load can occur rapidly, and the ammonium measurements are made in the effluent of the final settling tanks with a retention time of several hours, the response may not be fast enough. Because of this, an additional feedback control was used to speed up the response. The DO level in the last aerated zone corresponds to the oxygen demand in the preceding zones. By using a DO- feedback control from the last aerated zone, the DO set points adapts faster to changes in load.
PI controller 1 controls effluent ammonium with output $e1$. The choice of set point $r1$ is crucial in preventing excessive aeration during low loading conditions. During such conditions the effluent ammonium is often close to zero, and using this value as a set point would prevent the controller from decreasing its output signal additionally. To prevent this, $r1$ was set to a value larger than zero. PI controller 2 controls the DO concentration in zone 4 ($DO4$) with output $e2$. Set point $r2$ functions as the set point both to the supervisory DO- feedback controller and to the cascade control in zone 4. The reason for a separate control loop in zone 4 is to assure low DO concentrations in the internal recycle, preventing oxygenation of the anoxic tanks. The sum of output $e1$, $e2$ and an offset $C$ constitute the set point $r3$ for the cascade control in zone 1, 2 and 3. This offset facilitates the start up of the control strategy and renders a possibility of manual adjustments if needed. During the evaluation period of the strategy, $r1$ was set to 0.2 mg/l, $r2$ to 1.0 mg/l and $C$ to 1.4 mg/l.

![Diagram of control system](image)

**Figure 3** Separately controlled zones with ammonium- and DO- feedback.

**RESULTS AND DISCUSSION**

**Elevated DO concentrations**

With the new strategy the zones are separately controlled and the first three zones use the same DO set point. This decreases the airflows in the first zones and pushes the load toward following zones which effectively counteracted the DO surplus that occur at low loading conditions in the last zone. Figure 4 shows the DO concentration in the last zone in experimental and reference line during a period with low loading conditions. In the experimental line the DO concentration is close to the set point whereas the reference line shows elevated DO concentrations on numerous occasions. The DO set point in the last aerated zone was 1.0 mg/l in both lines. This is the value normally used at the plant for preventing oxygenation of the anoxic tanks.
Figure 4 DO concentrations in the last aerated zone during evaluation of the strategy.

Total airflows
The strategy gave a reduction of the total airflow of 18%. This reduction was mainly due to the better use of the aerated volumes. The large reduction of the airflows in the first zones was replaced by a smaller increase in the last zones thanks to the dynamics of oxygen transfer and growth rate function of the nitrifying bacteria. The supervisory controllers adapted the DO set points to the influent load giving additional reductions. Especially during weekends when the load often decreases and no personnel is at the plant, large savings were made. In Figure 5 the total airflows and the DO concentration in the first zone is shown during evaluation of the strategy. The adaptation of the DO set points by the ammonium- and DO- feedback together with the better use of the aerated volume resulted in a large decrease of the DO concentration compared to the reference line.

Figure 5 Total airflows and DO concentration in zone 1 during evaluation.

Treatment efficiency
The nitrification process deteriorates if the DO concentration is too low. For the suggested strategy to be useful, it is crucial that it do not lead to an increased mean effluent ammonium concentration. Since the strategy lowers the airflows and DO concentrations in the first zones the nitrification
processes are pushed down the aerated tank but because of the dynamics of the oxygen transfer and
the growth rate of the nitrifying bacteria the same amount of ammonium was removed in the tank.
In table 1 this is shown during the evaluation of the strategy. The supervisory controllers guarantee
that the load is not pushed too far down the tank and the ammonium concentration in the last zone is
kept at the same level as in the reference basin. It was expected for the effluent nitrate levels to
decrease because of simultaneous nitrification- denitrification in zone 1 and 2 where the DO
concentrations were lowered but this could not be seen. From table 2 it is clear how the strategy did
not decrease the treatment efficiency.

| Table 1 Ammonium and nitrate concentrations in experimental and reference line. |
|---------------------------------|--------|--------|--------|--------|
| Experimental line               | Zone 1 | Zone 2 | Zone 3 | Zone 4 |
| NH4-N (mg/l)                    | 4.0    | 3.6    | 2.5    | 0.2    |
| NO3-N (mg/l)                    | 0.6    | 0.3    | 1.2    | 3.5    |
| Reference line                  |        |        |        |        |
| NH4-N (mg/l)                    | 4.5    | 3.0    | 0.4    | 0.2    |
| NO3-N (mg/l)                    | 0.1    | 0.8    | 2.8    | 3.6    |

| Table 2 Treatment efficiency of experimental and reference line. |
|------------------------|-------|-------|-------|
| Experimental line      | COD (%) | Tot-N (%) | NH4-N (%) |
| Reference line         | 83    | 77    | 97    |
| Experimental line      | 82    | 75    | 99    |

Savings
Since the strategy was only tested in one line the absolute energy savings was fairly low. A yearly
savings of 9 200 € was achieved. When implemented to additional lines, the savings become
substantial. A reduction of the airflows of 18% corresponds to a yearly savings of approximately
55 000 € if used in all of the lines in the old part of the plant. A modified version of the strategy has
now been implemented to these lines (see section below) and will also be tested in the new part
during spring of 2009. Since the new part of the plant receives double the load, similar reductions of
the airflows would give substantial savings. Installation of the two additional DO probes needed in
each line will cost a total of 25 000 € and maintenance costs 5 700 € /yr so the pay off time is
expected to be less than one year.

Further experience from full scale operation
Since April 2008 a modified version of the strategy has been implemented to all of the lines in the
old part of the plant. Here the ammonium- feedback controller is no longer used. To prevent fouling
of the ammonium meter, it was placed in the effluent of the final settling tanks where the
concentration of suspended solids is low. When rapid changes of influent load occur the ammonium
meter will not detect the change quickly enough and counteract the DO- feedback controller which
responds much faster. A new type of ammonium meter less sensitive to fouling will be tested during
2009 and placed in a final aerated zone in the biological step. When comparing the total airflow to
the old part of the plant, before and after implementation of this strategy, a reduction of 26% is
seen, Figure 6. In Table 3 some key parameters are listed. From here it can be seen that the amount
of air consumed per volume of sludge in the aerobic tanks decreased by only 17%. At the same
time, the ammonium load relative the amount of sludge in the tanks was higher during 2008 but the
effluent ammonium lower. This indicates a higher efficiency of the nitrification processes.
The reason for the higher nitrate levels seen in the table, when comparing the results in 2008 with
2007, is higher levels of easily degradable COD in influent sewage during 2007. Since no external
carbon is used at the plant this has a large impact on the denitrification processes.
**Figure 6** Total airflow to all lines in the old part of the plant before and after implementation of the new control strategy.

**Table 3** Key parameters for comparison of strategies 2007 and 2008.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{air}$ (Nm$^3$/h)</td>
<td>11 700</td>
<td>8 600</td>
<td>-26%</td>
</tr>
<tr>
<td>Suspended solids (g/l)</td>
<td>2.64</td>
<td>2.36</td>
<td>-11%</td>
</tr>
<tr>
<td>$Q_{air}$/sludge amount (Nm$^3$/tonnes)</td>
<td>78 700</td>
<td>65 400</td>
<td>-17%</td>
</tr>
<tr>
<td>Influent NH$_4$-N (tonnes/d)</td>
<td>4.64</td>
<td>4.42</td>
<td>-5%</td>
</tr>
<tr>
<td>Influent NH$_4$-N/tonnes of sludge (kg/tonnes)</td>
<td>434</td>
<td>463</td>
<td>+7%</td>
</tr>
<tr>
<td>NH$_4$-N effluent (mg/l)</td>
<td>0.38</td>
<td>0.21</td>
<td>-45%</td>
</tr>
<tr>
<td>NO$_3$-N effluent (mg/l)</td>
<td>6.44</td>
<td>8.05</td>
<td>+25%</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The evaluation of the strategy showed that large reductions in air consumption can be made with a simple DO control strategy, enabling more sensitivity to changes of influent and making better use of the aerated volumes. The strategy made use of the higher driving force for mass transfer of oxygen at low DO concentrations and the dynamics of the growth rate function of the nitrifying bacteria by lowering the DO concentrations in the first zones and pushing the load toward the last zones. This gave substantial energy savings. The transfer of the load also counteracted the elevated DO concentrations that often occur in the last aerated zone during low loading conditions. Because of the supervisory feedback controllers the degree of treatment was unaffected.

**REFERENCES**


