The control of denitrification time in full scale by the automatic detection of the low nitrate bend in the redox curve

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ABSTRACT

A practical problem with using redox potential to control nitrogen removal in activated sludge is detecting the bend in the redox curve that occurs when the nitrate concentration is reduced to low levels. In this paper, a method for detecting the bend is proposed. The method is based on fitting a third-order polynomial to the whole redox curve during a denitrification period. The bend is then the point of inflection on this curve. This is the potential when the second derivative of the polynomial is zero. The practical application of the method is demonstrated in full scale. The method successfully detected the bend in about 90% of aeration denitrification cycles. However, this method gave no significant improvement in nitrogen removal and less than 4% reduction in electricity consumption when compared with control based on a fixed redox set point. Therefore, it is recommended that a fixed set point be used, as this is a much simpler and more robust method.

Key words | activated sludge, bend detection, control, nitrogen removal, redox

INTRODUCTION

Redox potential is used as a control parameter for nitrogen removal at many wastewater treatment plants (WWTP) (Charpentier et al. 1998). At these plants, the redox potential is most commonly used to trigger the restart of aeration in tanks where the process alternates between aeration and denitrification. One way in which this is done is that the plant operator chooses a redox set point that is a short distance below the normal level of the downward bend in the redox curve during denitrification. This bend indicates that the nitrate concentration is close to zero. A practical problem with this control method is that the redox potential at which the bend occurs changes from one hour to the next and from one day to the next. This means that the operator should consider changing the redox set point often. Alternatively, the operator can choose a set point below the lowest observed bend for a period such as the previous year and leave it there indefinitely. This second course of action leads to less than optimum control. However, it is sometimes chosen because it reduces the workload for the operator.

An improvement on the manual method of finding the bend and choosing a set point for the restart of aeration is an automatic detection of the bend. At least two groups, namely Sasaki et al. (1993) and Wareham et al. (1993), have done this. In both cases, detection of the bend depends on measuring the slope of the redox curve. Vanrolleghem & Coen (1995) compared the methods used. They wrote, “Both approaches use a moving window regression for noise rejection and slope calculation. Another similarity is that the slopes taken at different time instants are compared to decide if a local maximum is attained.” As the overall slope during denitrification is negative, then the maximum occurs...
when the slope of the redox curve is least negative. Normally this slope is still negative, but it can be on occasion both zero and positive.

The two methods differ in the way they compare the slopes at different time instants. Sasaki et al. checked the ratio of the two slopes, and Wareham et al. checked the difference between the two slopes. Vanrollegem and Coen concluded that the Sasaki method was able to detect the bend 2 to 4 minutes after it occurred, whereas the Wareham method required 8 to 9 minutes. On the other hand, the Wareham method resulted in more confident bend detection.

Plisson-Saune et al. (1996) used a pilot scale plant to test a control method based on automatic detection of the bends in the redox curve. They showed that a control system based on detecting these bend points was superior to a system based on fixed redox set points.

Prior to this investigation, bend detection by monitoring the slope of the redox curve was tested. Both the Sasaki and Wareham methods were used. With these methods, three parameters must be tuned in order to detect the bend. These parameters are the length of the curve within the moving window regression, the time difference between the two slopes that are compared, and the critical ratio or difference between the two slopes. Unfortunately, parameters that gave a dependable detection of the bend were not found for either of the methods. It was therefore decided to develop a more dependable detection method. This is the subject of the present investigation.

**METHODS**

The objective of a bend detection method is to find the point on the redox curve during denitrification where the slope is least negative. In the method devised, a third-order polynomial is fitted to the whole redox curve during a denitrification period. The polynomial is as follows:

$$E_m = At^3 + Bt^2 + Ct + D$$

where $t$ is the time from the start of denitrification, and $E_m$ is the measured redox potential. The start of each denitrification period is the time after aeration stops, when the oxygen concentration falls below a measurable level. The end of each denitrification period is the time when the redox potential drops below the set point for the restart of aeration. At the end of each denitrification period, the polynomial is fitted to the redox curve using the multiple least squares method. The second derivative of the polynomial is zero when the slope is least negative. This is the point of inflection. It is computed by the following equation:

$$t_i = -\frac{B}{3A}$$

where $t_i$ is the time at the point of inflection.

**Figure 1** shows an example of a redox curve and its polynomial fit. In this case, the redox potential at the point of inflection was $-25 \text{ mV}$. This potential is found by solving the third-order polynomial at the time of the point of inflection rather than searching the redox data. If the level were found by searching the data, then random changes in the redox potential would affect the outcome of the computation. The potential found by this method will be referred to as the denitrification level. Only if the following two criteria are met is it assumed that a denitrification level has been found:

1. $t_i$ must be greater than zero and less than the length of time of the denitrification period
2. the denitrification level must be within the range of the redox potential during the denitrification period.

To find the redox set point for the next denitrification period, $30 \text{ mV}$ is subtracted from the denitrification level. The number of mV to subtract should be large enough to ensure that in the following denitrification period the redox potential is below the denitrification level before aeration is restarted. If aeration starts before the redox potential drops
below the denitrification level, the level can not be found. In which case, the set point may “hang” at a high level while the true denitrification level continues to drop. Inspection of the redox curves indicated that the maximum downward change in the denitrification level from one cycle to the next was 30 mV. The complete set of rules for the set point is as follows:

- The set point is changed only if a denitrification level is found.
- If the set point is more than 30 mV below the new denitrification level the set point is increased by 4 mV.
- If the set point is less than 30 mV below the denitrification level then it is changed to the denitrification level minus 30 mV.
- If the set point is less than $-120$ mV it is increased to $-120$ mV.
- If the set point is greater than $230$ mV it is reduced to $230$ mV.

The bend detection method has been in use at the Ejby Mølle WWTP in Odense, Denmark, since July 7, 2005. Ejby Mølle is a Biodenipho plant serving the equivalent of a population of 210,000 (BOD load). About 25% of this load is industrial. Nitrogen removal at the Ejby Mølle plant is controlled using a combination of an ammonium measurement and the redox potential. When ammonium increases to more than 1.6 mg N l$^{-1}$, or when the redox potential drops below a low set point, aeration is started. When the ammonium concentration is reduced to less than 0.6 mg N l$^{-1}$, aeration is stopped. There is also a maximum cycle time of 90 minutes and a minimum aeration time of 4 minutes. Cecil (2003) provides more details on the control system used.

The plant has two sets of two aeration tanks. Each aeration tank is equipped with the following:

- Two Hach Lange Evita® oxygen meters
- One Broadley James redox electrode with a Yokogawa pH/ORP transmitter
- One Hach Lange Insitu® ammonium meter

In addition, nitrate is measured by a Scan Spectrolyser® in tank 1. The denitrification rate is then computed using this nitrate signal and an observer estimator (Dochain & Vanrolleghem 2001). This denitrification rate is used to compute the nitrate concentration in the other tanks.

The Broadley James redox electrode has an Ag/AgCl reference electrode. All redox potentials reported here are relative to this reference.

Every 10 seconds, a computer program gets the redox potential, the oxygen concentration, and the aeration status (on/off) from the plant’s SCADA program. At the end of each denitrification period, the program analyzes the curve. The computed denitrification level and a new set point are returned to the SCADA system. The bend detection program analyzes the redox curves from all four tanks. However, during the period reported here the redox set point was change only in tanks 1 and 2. Tanks 3 and 4 operated with a redox set point fixed at $-120$ mV. $-120$ mV is the lowest observed bend in the redox curve.

## RESULTS

During the period from July 7, 2005, to February 4, 2006, the rules for finding the set point were changed as experience with the system was gained. In particular, the maximum upward change of the set point was increased from 1 mV per cycle to 4 mV per cycle on February 4, 2006. This allowed the set point to follow the denitrification level most of the time. Different rules for checking whether a true denitrification level was found were also tried. For example a rule that rejected the polynomial fit if the root mean square of the errors was greater than 10 mV was used to begin with. However, it was found that the rules described above gave the best balance between certainty of detection and the frequency of detection failure. From February 4 to April 29, 2006, the rules for accepting the denitrification level and for finding the set point were as described in the methods section. The following is an analysis of this test period.

Figure 2 shows the redox potential, the denitrification level, and the set point in aeration tank 1 for 8 hours on April 20 to 21, 2006. Many of the aspects of the denitrification level detection and automatic set point adjustment can be seen in this figure. At 18:15, the denitrification level increased from $-40$ mV to $-30$ mV. However, in accordance with the rules, the auto set point increased only 4 mV. At the end of the next denitrification period, a new level was found just 1 mV higher than the previous level. Again, the denitrification level moved up only 4 mV. This process continued until 22:00
(at the denitrification level arrow) when no level was found. In this case, the time of the point of inflection was negative. The level was still more than 30 mV above the set point in the next two cycles; therefore, the set point continued to increase by 4 mV per cycle. At 23:05, the level dropped 15 mV and the set point was then less than 30 mV below the level. Therefore, the set point was also lowered in order to maintain the 30 mV gap. In the next cycles, the level moved up and down by about 20 mV, indicating that the method had difficulty finding the correct level.

Figure 3 shows the daily average denitrification level in each of the four aeration tanks for the test period. For the most part, the denitrification levels in the tanks follow each other. This indicates that the forces driving the change in the level apply to all the tanks at the same time. The high values for the level from April 13 to April 17 coincide with the Easter holidays.

There are no values for April 9 because operation of the computer on which the bend detection program ran was interrupted. When the program was on line again, the set points were the same as they had been when the program stopped. On the other hand, the denitrification level had decreased to well below these set points. Because the aeration restarts when the redox passes below the set point, the program was unable to find the new level. Therefore, the set point was adjusted manually. This was the only time during the test period when a manual adjustment was found to be necessary.

There appears to be a weekly cycle in the denitrification level shown in Figure 3. To verify this cycle, the average denitrification level for each hour of the week was computed. The result is shown in Figure 4. The value shown for hour 1 in Figure 4 is the average of the levels in all four tanks during the first hour of the 12 Mondays in the test period. Hour 168 is the average of the last hour of the 12 Sundays in the test period. It is clear from Figure 4 that there is both a daily and a weekly cycle in the level. This indicates that the load on the plant affects the denitrification level. Both Figures 3 and 4 also show that manual adjustment of the redox set point to follow the denitrification level closely is unfeasible.

Table 1 summarizes the effects of the automatic set point adjustment on the aeration and denitrification times in the aeration tanks. As the table shows, both the aeration and denitrification times are slightly smaller in the tanks with set point adjustment. Reducing denitrification time is the objective of the control system. Aeration time is also
reduced because the ammonium concentration does not increase as much during the shorter denitrification periods in tanks 1 and 2. Therefore, less time is required to reduce the concentration to the aeration stop concentration.

Because there is no separate measurement of the electricity used for aeration in the aeration tanks, a possible reduction in electricity consumption cannot be measured directly. However, the number of minutes each surface aerator is in operation is recorded. The number of aerators in operation is changed in order to control the oxygen concentration. The last column in Table 1 shows the percent of the operational capacity of the aerators used in each tank. 100% equals all six aerators in each tank running all the time. As it is, the tanks are aerated only about 30% of the day and five or six aerators are normally in use. The aeration percent in tank 3 is greater than in the other tanks due to a fault in one of the oxygen meters in this tank. Comparing tank 4 with tanks 1 and 2 shows that there was at most a 4% reduction in the capacity used. Therefore the electricity savings are probably less than 4%.

The next table, Table 2, shows the average ammonium and nitrate concentrations for the test period. The ammonium concentration is lower in tanks 1 and 2 than in tanks 3 and 4, but the difference is small considering the accuracy of the measurements. The nitrate concentration is probably the same in all 4 tanks.

As part of the daily routine at the Ejby Mølle plant, a 24-hour composite sample of the effluent from the secondary clarifiers is collected. This sample is analyzed for ammonium and, once a week, the sample is also analyzed for nitrate. Both analyses are performed at the plant with Hach-Lange simplified spectrophotometric methods. The average ammonium concentration during the test period was 0.2 mg N l\(^{-1}\), and the average nitrate concentration was 1.5 mg N l\(^{-1}\). The influent to the secondary clarifiers is the combined flows from the aeration tanks. Considering that there is some nitrification and denitrification in the secondary clarifiers, the values for ammonium and nitrate in Table 2 are not unlikely.

### DISCUSSION

The automatic set point adjustment had minimal and probably insignificant effect on nitrogen removal. The data from the test period support this conclusion. The primary reason is that the automatically detected set point does not significantly change the denitrification time. This is because the time required for the redox potential to drop from the denitrification level to the fixed set point in tanks 3 and 4 was only 2 to 4 minutes longer than the time required to drop from the level to the auto set point in tanks 1 and 2. This is shown in the fifth column in Table 1. 2 to 4 minutes is not enough to have a significant effect on the overall performance of the Biodenipho\(^*\) process, as shown in Table 2. This conclusion differs from the one reached by Plisson-Saune et al. (1996). This may be because Plisson-Saune et al. compared their results with a control system that does not perform as well as the control system based on ammonium measurements and a fixed redox set point, the system used in tanks 3 and 4 at the Ejby Mølle plant.

Better results may be obtained if the 30 mV gap between the denitrification level and the set point is reduced. The effect
Table 3 | Offline reanalysis of the redox data with different rules for changing the set point; the data is from all four aeration tanks for the test period

<table>
<thead>
<tr>
<th>Minimum difference (mV)</th>
<th>Reduction when level not found (mV)</th>
<th>Levels found (%)</th>
<th>Time from level to set point (min)</th>
<th>Average level (mV)</th>
<th>Average set point (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0</td>
<td>92</td>
<td>10.4</td>
<td>−14</td>
<td>−49</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>89</td>
<td>9.7</td>
<td>−13</td>
<td>−38</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>77</td>
<td>8.6</td>
<td>−6</td>
<td>−25</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>32</td>
<td>7.4</td>
<td>5</td>
<td>−10</td>
</tr>
<tr>
<td>30</td>
<td>4</td>
<td>92</td>
<td>10.5</td>
<td>−14</td>
<td>−50</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
<td>90</td>
<td>9.8</td>
<td>−13</td>
<td>−39</td>
</tr>
<tr>
<td>15</td>
<td>4</td>
<td>87</td>
<td>9.1</td>
<td>−10</td>
<td>−31</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>78</td>
<td>7.4</td>
<td>−3</td>
<td>−19</td>
</tr>
</tbody>
</table>

of reducing the gap between the denitrification level and the set point can be seen in Table 3. This table shows the results of an off-line reanalysis of the data for the test period using different rules for finding the set point. As expected, reducing the gap reduces the time between the level and the set point (column 4), but it also reduces the number of cycles in which levels were found (column 3). Levels were found in fewer cycles because there were more cycles in which the set point was above the denitrification level in the following cycle. Introducing a rule that the set point should decrease 4 mV for every cycle in which a level is not found noticeably improves the rate at which levels are found. This is shown in the last four rows of Table 3.

The rules of a 20 mV gap and a 4 mV decrease per cycle without a level found were tested in tanks 1 and 2 for 24 hours. This test resulted in a number of cycles in which aeration was restarted while the nitrate concentration was still high. This outcome was unacceptable, and the test was therefore abandoned. However, the rule for a 4 mV decrease per cycle without a found level was kept, along with the rule for a 30 mV gap. It is expected that this rule will prevent the set point from "hanging" above the denitrification level. The results of the reanalysis of the data indicated that this additional rule would not impair performance.

In the introduction, it was mentioned that consistent detection of the bend in the redox curve was not achieved using either the Sasaki method or the Wareham method. This may be because the denitrification periods at the Ejby Mølle plant are shorter than the denitrification periods employed by Sasaki et al. and Wareham et al. The shortest period reported by Wareham et al. was more than 1 hour; for Sasaki et al. it was slightly less than 1 hour. Furthermore, Sasaki et al. mentioned that detection of the bending point would be difficult with shorter denitrification periods. It may be may be the greatest strength of the method described here that it can detect the bend in 90% of cycles with denitrification times varying from 10 to 70 minutes.

CONCLUSION

This paper describes a method of analyzing the redox signal using a third-order polynomial fit to the whole redox curve during one denitrification period. This method finds the point of the redox curve with the least negative slope, which is referred to as the denitrification level. At the Ejby Mølle WWTP in Odense, Denmark, a computer program performs this analysis in real time. The set point for the restart of aeration after denitrification is then found according to a set of rules. The result is a set point 30 mV or more below the denitrification level. This is always below the low nitrate bend in the redox curve. The analysis is only performed once in each aeration–denitrification cycle and it is done immediately after aeration has been restarted. Therefore, the new set point is first available for the following denitrification period. On the other hand, the method detects the bend in 90% of cycles with denitrification times varying between 10 and 70 minutes. In this way, it may be superior to other methods of detecting the bend.

A comparison between a fixed low redox set point and the auto set point gave insignificant improvement in nitrogen removal and less than 4% reduction in energy consumption for aeration. Therefore, it is recommended that control based on fixed redox set points be used because this method is much simpler to implement than a system that automatically adjusts the set point.

REFERENCES