Exploiting online in-situ ammonium, nitrate and phosphate sensors in full-scale wastewater plant operation

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Abstract In-situ nutrient sensors are now a proven technology. Having ion membranes eliminates the need for ultrafiltration, and consequently the sensors can be located at suitable places in any of the reactors. This gives the potential for new control structures for the control of nitrification, denitrification, and phosphorus removal. In the paper some examples of such controllers are demonstrated as used in a full-scale wastewater treatment plant. A successful control implementation scheme at full-scale plants includes three steps: monitoring, experimenting and controlling. The benefit of implementing process control based on nutrient sensors is real: by implementing precipitation dosage control a savings of 41% compared to flow proportional dosage can be reached, while the savings compared to constant dosage is 73%. An increase in nitrate recirculation shows significant improvement in the nitrogen removal ability at very low cost. Reliable nutrient sensors are not the only prerequisite for a successful control system. The design of actuators, such as drives, compressors and valves, is often overlooked. Furthermore, the lower level controllers have to work properly before the more advanced controllers can work adequately. A collection of practical experience regarding such issues is given in this paper.

Keywords Control and automation; full-scale control implementation; in-situ nutrient sensors; nutrient removal

Introduction

With the commercialisation of in-situ sensors the location of nutrient measurement points is no longer restricted to the effluent from the secondary clarifier of a wastewater treatment plant. The sensors can readily be located directly in the process reactors, i.e. in-situ, providing timely data on the dynamics directly in the processes. Measuring nutrient concentrations in locations with high content of suspended solids – such as in the activated sludge reactors – is difficult using traditional automatic analysers. The required ultrafilter will frequently clog and require cleaning (see e.g. Devisscher et al., 2001). Due to the ion membrane used in an in-situ sensor (Lynggaard et al., 1996) the need for filtration has been eliminated and the servicing of the sensor is reduced to fifteen minutes once a month. This level of maintenance makes the sensor applicable outside the scope of carefully maintained research facilities, i.e. in normal full-scale wastewater plants.

Most controllers and control structures reported to date have been suggested based on simulation studies or pilot scale plants. Furthermore, the development and comparative testing of controllers and control structures have been accelerated by the definition of the benchmark simulation platform, see COST (2001), Pons et al. (1999), and Copp (2000). This type of test is useful to demonstrate that potential improvement exists. However only few implementations of nutrient sensor based control in full-scale plants have been reported, Nielsen Önnerth (1995, 1996) and Devisscher et al. (2001) being important exceptions. Some Scandinavian experiences are also reported in Olsson et al. (1997).

Measuring nutrient concentrations online and in-situ improves the potential to apply the sensors for process control. This makes it possible to implement many of the nutrient sensor based control strategies that have been proposed over the last twenty years, see e.g. Olsson
Implementing new control in full-scale plants raises additional challenges that should not be underestimated. A well functioning control system also depends on the quality of the basic controllers and the flexibility of the control handles. Furthermore, the sensor has to be placed at a representative location in the plant. Some of these practical issues are addressed in this paper. An effective implementation scheme is suggested that consists of three steps: 1) continuous monitoring of key signals to increase process understanding; 2) manual change of setpoints and sensor positions to observe the response; and 3) implementation of automatic process control based on experiences from steps 1 and 2, where the nutrient controllers are connected to the basic controllers. In that way setpoint values can be computed automatically. The steps are discussed in detail and examples of the three steps are given from the Källby full-scale wastewater treatment plant in Lund, Sweden (100,000 Personal Equivalents (PE)). See description of the plant in Ingildsen et al. (2001b).

**Sensor location and control structures**

The choice of sensor location reflects the choice of control structure. “The structural decision includes the selection/placement of manipulators and measurements as well as the decomposition of the overall problem into smaller subproblems (the control configuration)” (Larsson and Skogestad, 2000). In a pre-denitrification system a sensible decomposition of the problem is to divide it into the control of the nitrification and the denitrification processes. This leads to a limited number of options for sensor locations, as illustrated in Figure 1.

Generally the ammonium sensor is used for the control of the aerobic reactor(s) while the nitrate sensor is used for the control of the anoxic reactor(s). Depending on the location of the sensors they are the basis for feedforward or feedback control, see Figure 1. If possible, it is desirable to combine the two types of control. Feedforward control of nitrification can be based on ammonium sensors in the influent to the plant or the influent to the aerobic reactor. Based on the sensor information and a model, the need for aeration can be predicted. Feedback control can be based on sensors in the effluent from the aerobic zone or the secondary settler unit.

Feedforward control of denitrification can be obtained by locating the nitrate sensor at the influent to the anoxic reactor or in the head of the anoxic reactor. Generally this also requires a measurement of available easily degradable organic matter. Again this information in combination with model knowledge can provide a prediction of the required nitrate recirculation rate or the external carbon dosage. Feedback from the end of the anoxic reactor has been shown to be effective and not very sensitive to the exact nitrate setpoint,
which should be around 2 mg/l (Yuan et al., 2001). It has also been suggested that one can control denitrification based on effluent nitrate concentrations, see e.g. Lindberg (1997).

Generally, the advantage of feedforward is that it makes it possible to react early to disturbances. Ideally a feedforward controller can completely eliminate the influence of a disturbance, since the influent is measured. In reality the influence of the disturbance is attenuated, since the model and the measurement are never perfect. Feedback control can only react to the result of the process, making it less efficient in the reaction to disturbances. On the other hand, it provides a better accuracy. Thus feedforward gives a fast reaction, while the feedback delivers the accuracy of the control.

The closer the measuring points are to the processes to be controlled the better, therefore measuring directly in the reactors is preferred over measuring points in the effluent of settler units in most situations. The settler units introduce significant and varying time lags of the signal. The effect of a settler on the ammonium concentration can be seen in Figure 2, which shows the result from a simulation of a pre-denitrification plant during normal operation (the simulated plant is the plant used in the COST benchmark effort (COST, 2001). Compared to the ammonium concentration from the last zone the settler effluent signal is delayed due to the retention time and smoothed due to mixing in the settler. This hides important features of the signal. In the signal from the last zone it can be seen that the ammonium concentration becomes close to zero a large part of the time, indicating excessive aeration. This is hidden in the measurements from the settler effluent. Location in the reactor is of even higher importance regarding the control of nitrate recirculation and external carbon dosage. The most important issue regarding control of these is the full utilisation of the anoxic volume; thus the best sensor location is at the outlet of the anoxic zone. If the nitrate concentration is low or zero here the anoxic volume is not fully utilised. Settler effluent measurements of nitrate cannot reveal this.

Sensors for effluent compliance monitoring should naturally be located in the effluent of the plant, i.e. after the secondary clarifier and other post-processing reactors (e.g. post-precipitation or lagoons). At this location traditional automatic analysers with filters have been successful, as ultrafiltration is not required. However, at the Källby wastewater treatment plant it has been observed that events with raised levels of suspended solids, i.e. due to sludge escape, often cause the analyser in the effluent from the secondary clarifier to fail due to clogging. This is obviously not a problem with sensors with ion membranes.

![Figure 2 Comparison between ammonium signals from the effluent of the settler and from the outlet of the last aerobic zone](image-url)
Introducing nutrient sensors in full-scale plants

When introducing nutrient sensors in full-scale plants the goal is usually online process control to optimise process performance. The best implementation result with the fewest surprises is however achieved by applying the sensors in three steps of advancement. First the sensors are only monitoring the concentrations and thus providing increased understanding of the processes in the reactors. When operators have become acquainted with the signals and understand their meaning various setpoints can be changed manually (e.g. DO setpoints, recirculation rates, etc.) to observe the response. When processes and responses are well understood a suitable control structure can be developed and automatic process control is implemented.

Monitoring

Monitoring the course of the nutrient concentrations over the day gives insight into the magnitude of variations in zones and into the timely variation in the location of the processes. Figure 3 gives an example from a period where a nitrate, an ammonium and a phosphate sensor were located in the second last anoxic zone in the Källby WWTP. Some key observations are:

NH₄: the variance in ammonium concentration to the aerobic zones varies considerably and quite fast with varying daily patterns.
NO₃: part of the time the nitrate is zero or close to zero, showing that the anoxic zones are not used to their full capacity at all times.
PO₄: biological phosphorus release takes place when the zone becomes anaerobic (nitrate is gone). This shows that even at this late stage VFA is available for biological phosphorus release. It should be noted that the phosphorus release starts immediately, when the nitrate concentration has disappeared (applies only in the first half of the data series).

Especially during this phase it is a great advantage that the sensor can be moved around to find the most suitable location. At Källby WWTP a special rig was designed where the sensor was mounted on a metal rig that fitted over the concrete basin walls, which made it easy to move the sensors around to test various locations.

Experimenting

The above analysis showed that the anoxic zone was not fully utilised. Therefore it was assumed that a larger internal recirculation would lead to an increased removal of total nitrogen. In order to improve the utilisation of the anoxic zones the nitrate recirculation was

Figure 3 Observation of the nutrients concentrations over time
increased to its maximum value in one of two parallel identical biological lines (line 3). This leads to a significant and immediate improvement in the effluent of total nitrogen of approximately 2 mg/l, see Figure 4, where the two parallel lines are compared. The idea of making an experimenting period is to get a feel of the response of the various control handles. Simulation programs (even roughly calibrated) for the plant can be very helpful when predicting or interpreting the result of such changes. Benefits from online sensors can in fact be obtained at two levels, either by static optimisation, where e.g. a constant DO set-point is changed from 2.5 to 2 mg/l or the internal recirculation is increased as shown above. This is manual setpoint change and may often lead to considerable improvement in operation. The next step is the automatic change of setpoints which can take place in a more continuous and frequent manner, which is discussed below.

**Automatic process control**

In Ingildsen et al. (2001b) an automatic process controller for dynamic control of the DO setpoint based on a combination of feedforward and feedback is suggested and tested in the Källby wastewater plant. The control of chemicals dosage for phosphate precipitation in a post-precipitation step is another process where great improvements can be achieved by nutrient sensor based control. Three different control structures for precipitation control has been tested: flow proportional control, phosphate proportional control and feedback control with an effluent phosphate setpoint. The flow proportional control showed a rather poor performance as a large variation in the effluent phosphate concentration was observed, see Figure 5. Sometimes the concentration is too high, i.e. higher dosage is needed and sometimes it is zero, meaning that too much is dosed. One problem with this type of control is that a varying efficiency of the biological phosphorus removal in the preceding activated sludge system lead to a varying inlet concentration of phosphate to the precipitation reactor.

Load proportional control and feedback PI control both show good results as can be seen in Figure 6. The feedback controller is implemented by locating the sensor in the end of the flocculation chamber. Because the precipitation reactor is similar to a plug flow reactor, leading to a delay in the response of the signal to the dosage, a relative low gain has to be applied in the controller to avoid instability. The integral time was chosen to be approximately 60% of the average retention time in the reactor. This showed a satisfactory performance during average flow. However, during extreme rain the retention time
decreases and thereby the deadtime, which leads to a decrease in controller performance. Dead time compensation by applying a Smith predictor controller may improve performance but still remains to be tested. An alternative is to apply a varying integration time constant depending on the influent flow.

The controller is based on the phosphate concentration while most effluent permits are defined in terms of total phosphate. At Källby WWTP it was, however, found that total phosphorus and ortho-phosphate are linearly correlated, with a regression value of 0.97. The regression was based on 28 samples, see Figure 7. This means that it is possible to control the process towards a certain phosphate setpoint and be reasonably sure that total phosphorous will be in compliance.

An estimate of the savings obtained by these two types of control compared to flow proportional control, can be found by finding the maximum ratio between influent flow and dosage flow. This level should be applied at all times in order to ensure proper removal during flow proportional control. The saving based on two weeks of data was 41%. The savings are even larger when compared to a constant dosage strategy, where the maximum dosage from the full month of operation should be applied at all time. In this case the saving amounts to 73%. Obviously this leads to a considerable saving in chemicals. However, what may be even more important is the decrease in production of chemical sludge. In Devisscher et al. (2001) this is reported to have doubled the value of the chemicals savings. On top of that an important benefit is that plant staff do not need to worry when being checked for compliance; the compliance is ensured directly. This is particular true for the feedback control structure, which additionally has the advantage that it is not sensitive to fluctuations in concentration of the dosage chemicals.

Figure 5  Result of flow proportional control of dosage of phosphate precipitation chemicals

Figure 6  Phosphate concentration at the end of the mixing chamber in a post-precipitation unit
Issues to be addressed in full-scale implementation

Full-scale implementation of automatic control is more complex in nature than modelling and even pilot-scale plants. Below a list of the most important issues as experienced during full-scale experiments at Källby wastewater treatment plant is provided. The problems are of general nature and apply to many plants.

1. **Actuators** may limit the ability to control, i.e. by having a too low maximum or too high minimum capacity. This is probably the most fundamental barrier for more widespread acceptance of new control strategies, and many existing wastewater treatment plants are not designed for real-time control. The ability to adjust the control handles in a continuous way, e.g. by using variable speed electric drives, is also of paramount importance to get a smooth and varied control. Often valves are poorly designed for control. One problem may be their nonlinear behaviour. Another problem is that their operating range for control is only a fraction of the range of the valve. This makes the control difficult and inaccurate. A more detailed analysis of these issues is found in Olsson and Newell (1999, Chapter 24).

2. **Lower level controllers** should be well functioning before implementing higher level control. This is of fundamental importance in process control. A proper functioning dissolved oxygen control is a pre-requisite for nutrient control in aerators. Again the functioning of the actuators is often overlooked. For example, the compressors have to be able to deliver quite variable airflow rates in order to ensure energy savings. In addition, the airflow valves to the aerators have to be properly controlled. In Källby WWTP the dissolved oxygen control manages to keep the DO standard deviation at around 0.12 mg/l.

3. The design of controllers requires a clear control performance goal that fits the compliance criteria. E.g. if compliance is defined as weekly averaged concentrations it is not necessary to remove normal diurnal variation in the effluent.

4. **Quality assurance** of all measurements and actuators is a prerequisite for correct interpretation of the process behaviour. There are many possible errors that can occur in the line from process to sensor to controller and to actuator. Examples are sensor fauling, wrong wiring, defect pumps etc. Details of this analysis are found in Olsson and Newell (1999, Chapters 22–24).

5. Be certain that the measurement is representative for the process in focus. One example
of a wrong location of sensors stems from the Källby wastewater treatment plant, see Figure 8. Here the nitrate sensor was located five metres from the inlet of the first aerobic zone. The response of the nitrate signal was not quite as expected. After some time it was realised that the nitrate concentration was strongly correlated with the dissolved oxygen concentration in the first aerobic zone. To check if the effect could be due to dissolved oxygen entering the zone against the wastewater stream causing nitrification in the anoxic zones a handheld DO meter was used. DO could be detected in an area of approximately 30 m² before the inlet of the aerobic zone in concentrations up to 1.5 mg/l. Therefore the nitrate sensor was moved further 10 metres upstream, away from the aerobic zone.

6. Beware that the processes develop in several time scales. The sludge properties that change slowly are particularly important to monitor. One important property is the settling. The sludge volume index (SVI) or the diluted sludge volume index (DSVI) are good parameters to monitor for this purpose (Jenkins et al., 1993). Changes in the SVI are often related to floc forming properties, in case of troubles with this parameter microscopic analysis is required to identify the filament in order to apply the proper remediation. Another important issue about the sludge is its nitrifier content, which is primarily affected by the amount of nitrified ammonium, see (Ingildsen et al., 2001b). The more that is nitrified the higher the concentration of nitrifiers; this is naturally strongly linked to the aerobic sludge age.

Other experiences of implementation are found in Nyberg et al. (1993).

Conclusions

The application of ammonium, nitrate and phosphate analysers for monitoring the effluent concentrations have become standard in many plants over the last five to ten years (Jeppsson et al., 2001). The next step is to use the information for automatic process control. In-situ sensors with their ability to measure directly in the process reactors are well suited for control purposes and provide rapid information of the relevant concentrations. An implementation scheme for full-scale plants is suggested here that involves three steps: monitoring, experimenting and automatic control. Examples of each step are given from a Swedish WWTP, where the benefits have been improved nitrogen removal and savings in chemicals for phosphate precipitation. Additionally some practical experience is mediated. Today’s online in-situ sensors have reached a development level where it is possible to exploit the potential for optimisation of full-scale plant operation, not least due to the low level of maintenance required.

Figure 8 Nitrate sensor location should be several metres away from aerobic zone
References


