Biosensing activated sludge

Optimal operation of wastewater treatment plants depends on a full understanding of the many biological interactions that take place. **Krist Gernaey, **Britta Petersen**, **Jean-Pierre Ottoy** and **Peter Vanrolleghem** look at the growing role of biosensors, including their use with toxic wastewaters and measurement of sludge settling characteristics.**

Biosensing of activated sludge is the measurement and interpretation of the biological response of activated sludge to a known disturbance. The purpose of biosensing, on-line at the full-scale plant or off-line in lab-scale tests, is to obtain specific information about one or more activated sludge processes which can serve as plant performance indicators. Such information could include concentrations of readily biodegradable organic substrate fractions; concentrations of nitrogen components; toxicity of wastewater; degradation capacity of the sludge; settling characteristics and so forth.

The disturbance the activated sludge is most often subjected to takes the form of a substrate addition (organic carbon; nitrogen; mixtures; wastewater and so on). The measurement typically takes place in a small reactor filled with activated sludge previously sampled from a treatment plant. The measurement device within this reactor vessel can be a simple probe, for example a dissolved oxygen or pH electrode, but it can also be a more complicated flow injection analysis system. Processing and interpreting the recorded response, which is already done automatically in several systems, can be based on a simple regression analysis or an advanced model-based data interpretation procedure.

Biosensing COD and N removal processes

When combined COD, N and P removal in wastewater treatment was introduced, it significantly increased the complexity of the biological interactions. This in turn created a need for better understanding of the performance of the biological processes, and also for more advanced control.

In the field of biosensing COD and N removal processes, development has moved in two directions. First, on-line sensors were developed to obtain information on wastewater and sludge characteristics, which can be important in controlling the wastewater treatment plant.

Secondly, the introduction of more advanced dynamic models - like the Activated Sludge Models - which simulate COD, N and P removal in activated sludge plants (Henze et al. 1987), created a need for adequate tests to characterise wastewater and activated sludge. Research here is concentrating on developing methods and techniques, both on-line and in lab-scale tests, which can provide the information needed for model calibration. Indeed, the quality of the model predictions is strongly dependent on the quality of model calibration.

Respirometry

Respirometry - the measurement and interpretation of activated sludge oxygen uptake rate - is one of the most popular techniques for studying the characteristics of wastewater and activated sludge biodegradation kinetics (Brouwer et al 1998; Coen et al 1998; Kappeler and Gujer 1992; Kristensen et al 1992, Spanjers and Vanrolleghem, 1995 among others). There are many different reasons for that (Vanrolleghem et al 1999):

- A main goal in biological wastewater treatment is the reduction of the biological oxygen demand of the wastewater .
- Activated Sludge Model No 1 was primarily developed to provide a good description of sludge production and consumption of electron acceptors (oxygen and nitrate) during degradation of organic substances.
- Respirometry is a very sensitive method for studying biological processes. Changes in oxygen concentrations in the order of ten parts-per-billion can be monitored at high frequencies in samples which have not been pretreated.

A detailed description of different respirometric techniques can be found in the IAWQ Scientific and Technical Report 7, Spanjers et al (1998).

Interpretation of respirometric data is often model based. One good example of this is given in Coen et al (1998). Here, the RODTOX respirometer (which is built around a continously aerated batch reactor) had been installed on-line at a full-scale, industrial wastewater treatment plant which has COD removal but no nitrification. The respirometer is used for monitoring the readily biodegradable organic substrate.

The paper illustrates how an on-line model-based approach can be applied to interpret these data. In Figure 1 a typical sequence of raw dissolved oxygen data for eight batch experiments with wastewater, four calibration experiments and one decantation cycle is given. Each of the wastewater oxygen profiles contains three sharp 'shoulders', which indicates that the wastewater contains three main wastewater fractions. Models which can describe the wastewater and calibration profiles were developed and applied to the on-line data using an on-line version of a parameter estimation program (Mosifit). Results, including the total concentration of readily biodegradable carbon and composition ratios between the three wastewater fractions, are illustrated in Figure 2.

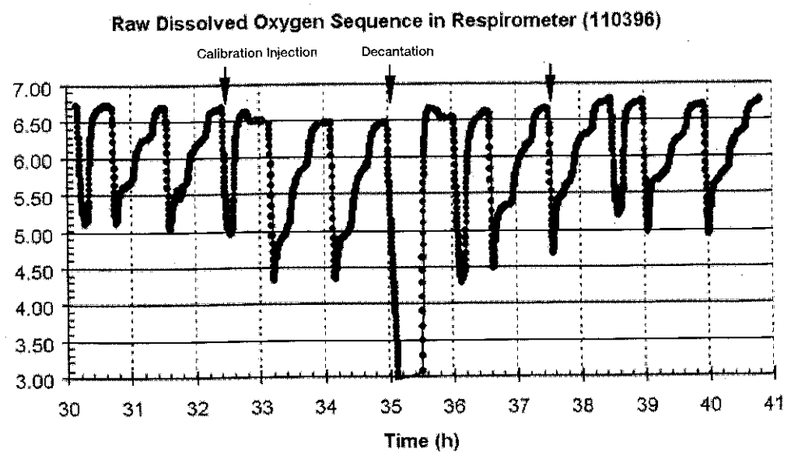


Figure 1. Dissolved oxygen data from the RODTOX respirometer installed on-line at the influent of industrial wastewater treatment plant (Coen et al., 1998).

Other methods

Many other methods beside respirometry have also proved useful in characterising wastewater and sludge kinetics. Measurements of ammonium uptake rate (AUR) or nitrate uptake rate (NUR) have been used to characterise the nitrogen removal processes in lab-scale experiments. However, application of AUR and NUR on-line is more problematic, since ammonium and nitrate sensors are not as robust as, for example, a dissolved oxygen measurement.

A titrimetric method, in which the proton consumption or production rate is monitored in a reactor vessel, has recently been successfully applied to the characterisation of nitrification (Gernaey et al 1997) and is currently being developed to characterise other processes (Gernaey et al 1999). This method has proven to be rather simple and robust, and prototypes are currently being tested in on-line measurement of nitrification capacity. The first data, collected over one month in the autumn of 1998, are illustrated in Figure 3. The decreasing trend can be explained by a slow temperature decrease in the activated sludge tank, which negatively influences the nitrifying population.

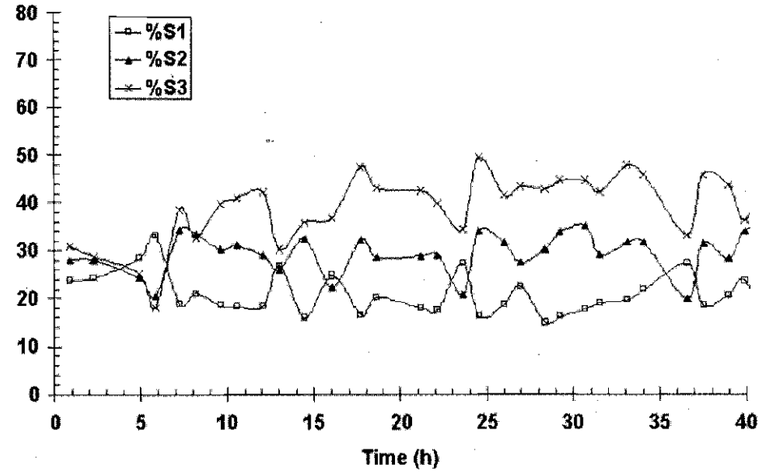


Figure 2. Estimation of wastewater fractions with an on-line model-based approach (Coen et al., 1998).

Developments are also under way to combine an already advanced respirometric technique - the hybrid respirometer (Vanrolleghem et al 1998) - with the titrimetric technique. The aim is to apply this combined respirometric-titrimetric method to enable more accurate and efficient characterisation of different activated sludge processes.

The hybrid respirometer consists of an aerated open batch reactor with an oxygen probe, connected by a pump to a closed reactor which also has an oxygen probe installed. The activated sludge is continuously pumped from the open to the closed reactor. The principle is illustrated with a simple experiment in which acetate and ammonium are added simultaneously.

In Figure 4, the two oxygen curves from the open and closed reactor respectively are illustrated. The difference between the two curves is due to the retention time in the closed reactor. Based on a simple mass balance across the closed reactor the OUR can be calculated - this is also illustrated in Figure 4.

It is clear from both the oxygen and OUR curves that the profile can be divided into two parts. In the first, both acetate and ammonium are degraded simultaneously. In the second phase only the degradation of ammonium continues. It should be noted that different levels of information can be obtained from these oxygen curves. Not only does the mass balance - using both oxygen measurements - across the closed reactor give information on OUR, but the oxygen sag observed in the open and aerated reactor gives information on its own, comparable to the information derived from a RODTOX. This shows that the sensor data can be combined to yield more accurate process characteristics.

Figure 5 provides information from the simultaneous titrimetric measurements. In the titrimetric method, the pH is kept constant (within a band of +/-0.03) using an accurate pH controller, and the acid and base dosages required to keep this pH are recorded. Generally, nitrification produces acid, which means that base must be added to keep a constant pH. In contrast, uptake and

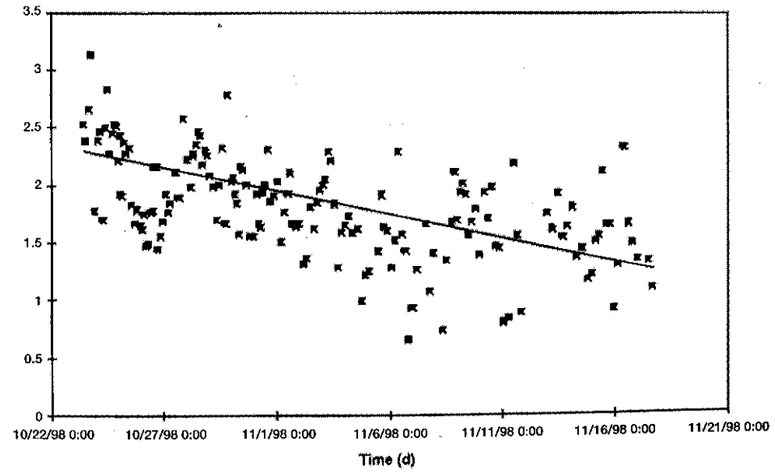


Figure 3. Nitrification capacity measured for a municipal treatment plant with an on-line titrimetric sensor.

degradation of acetate consumes acid.

During the first part of the experiment, these two processes (nitrification and acetate degradation) do indeed almost compensate for each other, and only a small amount of acid has to be added to maintain a constant pH. However, as soon as acetate is degraded, base must be added to compensate for the protons produced during the nitrification process. Finally, it can be seen that there is a clear bend in the base curve at the nitrification end-point. In summary, such titrimetric curves can provide important information on the different processes and, combined with respirometry, it becomes a powerful and very information-rich method for characterising biological wastewater treatment processes.

Biosensing toxic wastewater

Toxic wastewaters can be an important and unexpected source of problems at activated sludge plants. Protecting a plant against potentially toxic wastewaters has consequences for treatment plant design, typically in increased reactor volumes or the need for buffer/calamity tanks. Toxic wastewaters are generally related to industrial activity and, in the best situation, they are treated at source. However, this is often not the case. This means rapid and simple on-line test methods are useful to detect increased acute toxicity in the wastewater.

Several standardised toxicity test methods are available on the market, for instance using luminescent or immobilised bacteria. The disadvantage of these methods is that the bacteria used may not accurately represent the situation at a specific wastewater treatment plant. The best correlations between the results of a toxicity test and the real behaviour of the activated sludge of the plant to be protected are obtained when the activated sludge itself is used in toxicity tests.

Different respirometric applications have been designed which use the activated sludge to detect wastewater toxicity. As discussed, respirometric measurements can be used to monitor the response of COD degrading as well as nitrifying bacteria. In recent years attention has been increasingly paid to nitrifying bacteria in the sludge as indicator organisms for these tests because the nitrifiers are, for many wastewater components, the most sensitive activated sludge bacteria (Blum and Speece, 1991).

Detection of toxic wastewater using respirometry is mostly achieved by comparing the response of the sludge in the presence of wastewater with the response obtained for a non-toxic reference substrate. There are several examples where the use of on-line biosensors has been shown to be useful in detecting the presence of increased acute toxicity in wastewater (see box 'On-line toxicity detection of toxic wastewater: a case study', Vanrolleghem et al 1996).

Nevertheless, the operation of biosensors in toxicity testing can be further improved to maximise the amount of information available to the treatment plant operator. A treatment plant operator confronted with a toxic alarm generated by a biosensor gets little or no information about the nature of the toxic compound in the toxic wastewater. The operator may not know how to react to protect the plant most adequately. A few simple tests on the activated sludge in the biosensor could, for example, help to discover whether the toxicity can be reduced by dosing activated carbon, or if the toxic compound can be degraded by the sludge within a reasonable time (see box 'Nitrification inhibition by phenol').

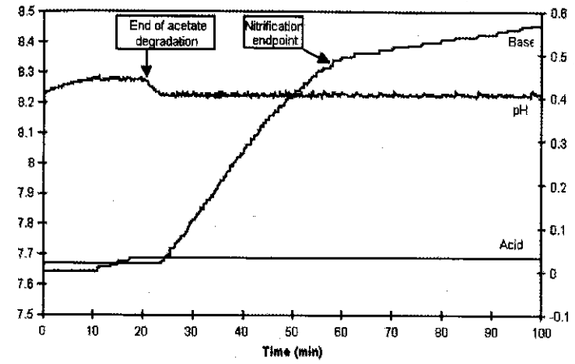
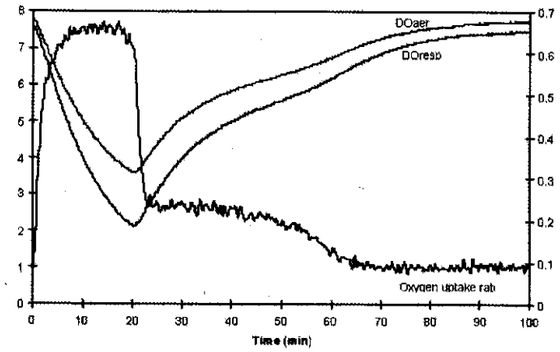
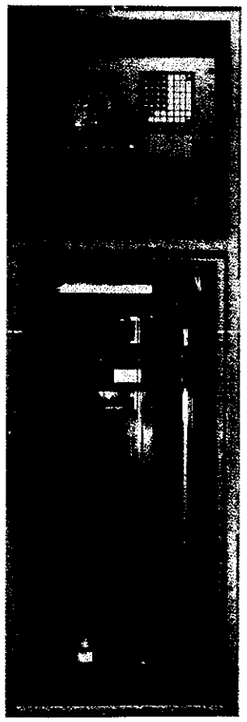


Figure 5. Example of titrimetric data for the experiment described in Figure 4.



ABOVE: Figure 4. Example of hybrid respirometer data obtained after addition of acetate (30mg COD/l) and ammonium (2mg N/l) at t=0.
RIGHT: Settleometer to monitor sludge sedimentation characteristics.



Biosensing sludge settling characteristics

The final sedimentation step is generally considered one of the most crucial processes in an activated sludge plant. Sludge sedimentation problems and sludge wash-out are regularly reported at many treatment plants, but the causes are often poorly understood. Secondary clarifier efficiency is dependent on the sludge sedimentation characteristics, the sludge concentration and the hydraulic load.

Sludge sedimentation is traditionally characterised through a laboratory batch sedimentation experiment, from which the sludge volume index (SVI, expressed in ml per gramme of sludge) is obtained. Since SVI determinations are infrequent (typically once per day), and experimental

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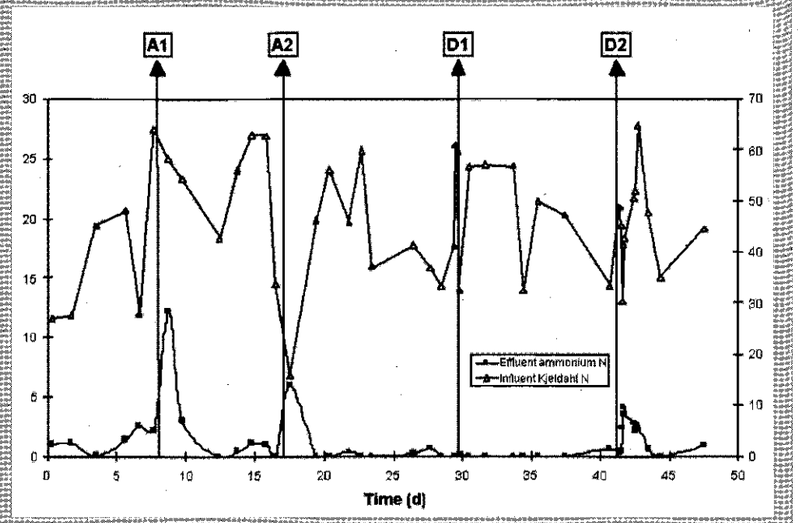
On-line toxicity detection of toxic wastewater: a case study

A respirometer, in this case the RODTOX, was installed at the intake of a treatment plant. Influent was regularly dosed into the reactor vessel contained in the biosensor. Toxicity of the influent was evaluated by comparing the respirometric data obtained during two calibration cycles before and after the addition of an influent sample. A 20% reduction of the degradation capacity for the reference substrate which is added during the calibration cycles was considered to be an indication of increased acute toxicity in the wastewater.

During the first phase, the normal treatment plant influent was monitored. An alarm was generated twice (events A1 and A2). Both alarm situations were followed by an increase in the effluent NH_4^+-N concentration, an indication that nitrification in the treatment plant was indeed being inhibited. Kjeldahl influent nitrogen data show that the increase was not due to an increased loading.

In a second experimental phase, the reliability of the respirometer for toxicity detection was tested by deliberately making the wastewater toxic using creoline. In a first experiment (event D1) the toxic compound dosing was stopped immediately after it was detected in the influent. This simulates a control strategy in which the toxic wastewater is pumped into a 'calamity basin' when increased toxicity is detected.



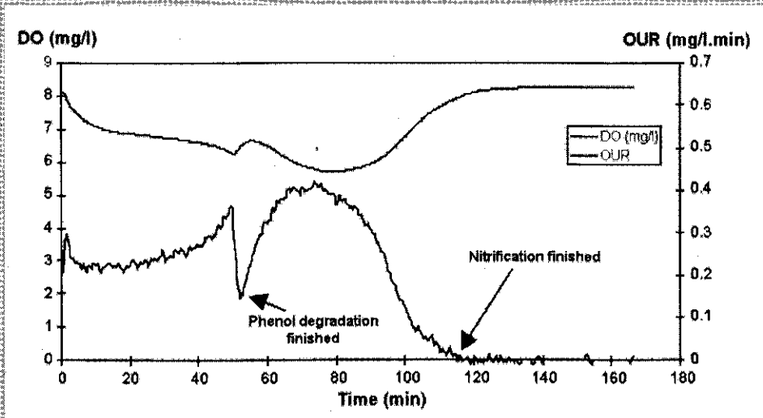
Influent Kjeldahl nitrogen and effluent NH_4^+-N measured at a hospital wastewater treatment plant during toxicity detection experiments with the RODTOX biosensor (*Vanrolleghem et al., 1996*)

Creoline reached a maximum concentration of 5 mg/l in the activated sludge. Toxicity detection occurred sufficiently promptly, proved by the fact that NH_4^+-N removal was not affected. In a second experiment (event D2) the addition of toxic wastewater was continued even after detection of the toxic pulse, until deterioration of the effluent quality was observed. Creoline dosage was stopped when effluent NH_4^+-N concentrations increased (in this scenario, creoline concentration in the activated sludge tank reached 25 mg/l).

Nitrification inhibition by phenol

Phenol is one of the best known examples of a toxic, but biodegradable compound. In a preliminary experiment it was confirmed that phenol could be degraded by the activated sludge sample in the respirometer. The respirogram (an OUR profile as function of time) in the figure shows the response of nitrifying activated sludge on adding a mixture of phenol and ammonium at time = 0. In the first phase, nitrification is inhibited but the phenol is degraded, albeit slowly. Phenol degradation speeds up after about 30 minutes and comes to an end after about 50 minutes, as can be seen from the sharp decrease in the OUR profile. As soon as phenol degradation is finished, nitrification increases to the same rate as before the phenol addition (a separate experiment with ammonium addition was performed before this combined experiment; these results are not shown).

For a treatment plant this specific experiment tells the operator that nitrification would be inhibited but would recover easily when the phenol degradation is finished. The operator can, for example, stop the sludge waste pump to ensure that too much nitrifying sludge does not wash out while the nitrification is inhibited.



Response of the RODTOX respirometer to the addition of a mixture of phenol (15mg/l) and ammonium (5mg N/l)

conditions often differ from the real conditions in the secondary clarifier, the value of the obtained data is limited. SVI values also depend on the sludge concentration, unless the sludge sample is diluted.

The limited availability of sludge sedimentation data seems contrary to the importance of the sludge sedimentation process. A sludge blanket height detector installed on the secondary clarifier can help to avoid sludge wash-out, but it still does not identify why the sludge wash-out occurred. Sensors have only recently been developed to characterise sludge sedimentation characteristics on-line (with a measuring frequency of one sample per hour) through automated batch sedimentation experiments in a glass measuring cylinder (see photo), under conditions that approach those in the secondary clarifier. During the in-sensor-experiment, the evolution of the height of the sludge blanket is monitored. Figure 6 shows an example of sludge sedimentation curves measured in the presence of increasing polymer concentrations. The positive effect of the polymer is obvious: the sedimentation velocity increases from 1.8 to 6m/h.

From the resulting sludge sedimentation curve, the maximum sedimentation velocity and the SVI can be readily obtained. The applications for a 'settlometer' are very diverse (Vanderhasselt, 1999): on-line detection of variations in sludge sedimentation velocity in the secondary settler; determination of the optimal dosage for additives to improve sludge sedimentation characteristics (such as polymer); extraction of settling velocity function parameters from sedimentation curves and so forth.

A recent example of a process control application for the settlometer is in the control of polymer addition to improve sludge sedimentation (Vanderhasselt et al., 1999). To achieve this, batch settling curves were first recorded for different sludge and polymer concentrations. The phenomena observed in the experimental phase by the sludge sedimentation monitor were successfully implemented in a one-dimensional dynamic settler model. With this model, the effectiveness of different control strategies was assessed using, for instance, the sludge blanket height measured in the settler. It was found that polymer only needed to be dosed when the sludge blanket height exceeded a certain level. A polymer dosage reduction of 90% could be obtained, in contrast to the pre-existing situation which had seen continuous polymer dosage.

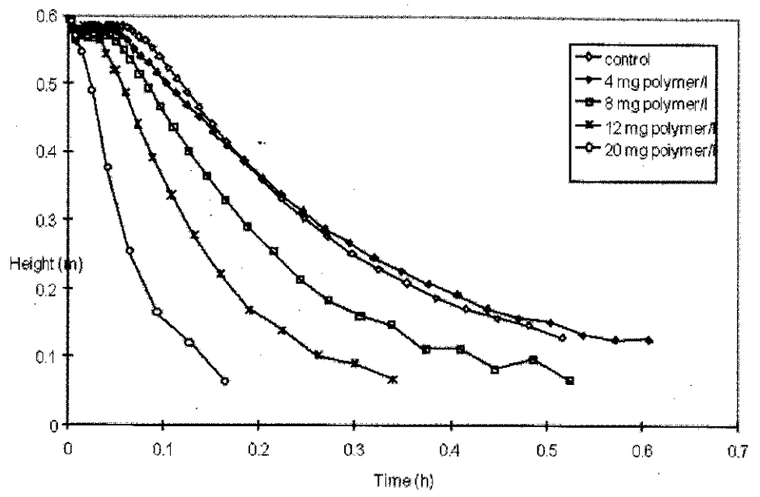


Figure 6. Sludge sedimentation curves for different polymer dosages added to sludge from an industrial wastewater treatment plant, (SS=6.1 g/l, the polymer dosages are cumulative) (Vanderhasselt, 1999).

Conclusions

Full understanding of the complicated biological interactions in a wastewater treatment plant is essential to optimise treatment plant operation, reaching a good effluent quality at minimum cost. Biosensing techniques as described above are one of the cornerstones of these developments. ■

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