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# OXYGEN UPTAKE RATE MEASUREMENTS FOR APPLICATION AT WASTEWATER TREATMENT PLANTS

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## Abstract

Increasing discharge demands put higher pressure on process optimisation and control of the wastewater treatment plant performance. For evaluation and regulation of the process performance, oxygen uptake rate (OUR) measurement is a useful tool. In this paper one way to perform oxygen uptake rate measurements is described. Possible applications of the method for wastewater treatment plants are presented and associated questions and problems are highlighted. Benefits and drawbacks of the OUR method are discussed. In order to obtain more detailed information about the wastewater, examples of complementary methods to the OUR method are exemplified.

*Key words* – aerobic degradation, activated sludge, organic degradation, oxygen uptake rate, respirometry, wastewater

## Sammanfattning

Ökade utsläppskrav kräver ytterligare optimering och kontroll av processerna på avloppsreningsverken. För utvärdering och reglering av reningsverkens processer är mätningar av syrerespiration ett användbart verktyg. I denna artikel beskrivs ett sätt på vilket man kan genomföra syrerespirationsmätningar. Möjliga sätt att applicera metoden på reningsverk presenteras och frågor omkring metoden lyfts fram. Metodens fördelar och nackdelar diskuteras. Dessutom ges exempel på andra metoder som kan kombineras med syrerespirationsmätningarna för att erhålla en mer komplett bild av avloppsvattnet eller de biologiska processerna på reningsverket.

## Introduction

Organic material in wastewater is removed in order to reduce oxygen consuming substances in the recipient and it is performed by bacteria at wastewater treatment plants (WWTP). In activated sludge the biomass consists of different types of bacteria. The heterotrophic bacteria are together with other microorganisms responsible for the degradation of the main organic material.

The aerobic degradation process of organic material can be determined by measuring the oxygen uptake rate (OUR) for the microorganisms. The main part of the organic material in the wastewater is degraded in aerobic environments, even though some is used for nitrogen removal in the denitrification step and some is reduced by the biological phosphorus removal process.

Increasing discharge demands put higher pressure on process optimisation and control of the wastewater treatment plant performance. For evaluation and regulation of the process performance, oxygen uptake rate measurement is a useful tool. Oxygen uptake rate measurements can provide much information concerning treatment plant performance, wastewater characteristics, degradability of special concentrated streams as well as parameters needed for mathematical models, in order to predict possible optimizations of a treatment plant. In addition it is useful for daily operation control. To extract broader information of the activated sludge, wastewater or the process performance, the OUR measurements are beneficially combined with supplementary methods and additional analysis.

The oxygen uptake rate has previously been described

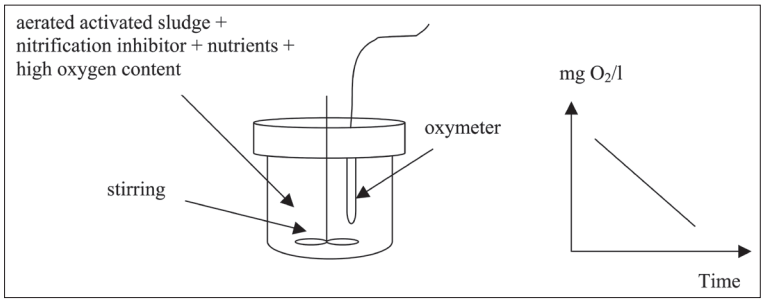


Figure 1. *Illustration of the principle of the OUR measurements.*

by many authors and has been used for research at wastewater treatment plants for many years. This paper will not try to review all about the OUR method, instead possible performance strategies of a simple OUR test for WWTPs is presented. In addition possible applications of the method will be described.

## Method

### Measuring the oxygen uptake rate

The oxygen respiration by heterotrophic bacteria is a process easy to measure. By determination of the oxygen consumption during a limited period of time, the oxygen uptake rate (OUR) can be calculated. The measurements can be performed in various ways which has been described in detail by many authors (e.g, Kappeler and Gujer, 1992, Kristensen et al., 1992, Roš, 1993 and Spanjers et al., 1998). Many types of equipment are available on the market, but the fundamental idea of the test used in this study is illustrated in Figure 1.

For OUR measurements, aerated activated sludge containing necessary nutrients and nitrification inhibitor (in order to eliminate oxygen consumption due to nitrification) is used. During some minutes the decrease of oxygen concentration in the sludge solution is registered. The relationship between the decrease in oxygen concentration and time is normally found to be linear as in Figure 1 and the oxygen uptake rate is determined by calculations of the slope of the curve. If the oxygen uptake rate is related to the volatile suspended solids (VSS), the specific oxygen uptake rate is obtained.

By alternating the aeration of the sludge in intervals it is possible to follow the OUR during a longer period. If the oxygen concentration is followed, the plotted measurements results in a curve as the one shown in Figure 2. When the decline in oxygen concentration is registered and the specific OUR is calculated, it is plotted against the time as shown in Figure 3. Figure 3 shows the corresponding specific OUR every 10 minute for activated sludge from Källby WWTP in Lund with addition of acetate. A graph like this is called a respirogram.

### How to interpret the measurements?

The OUR measurements are not very difficult to perform practically, but demands more effort in order to interpret the results into useful information. Figure 3

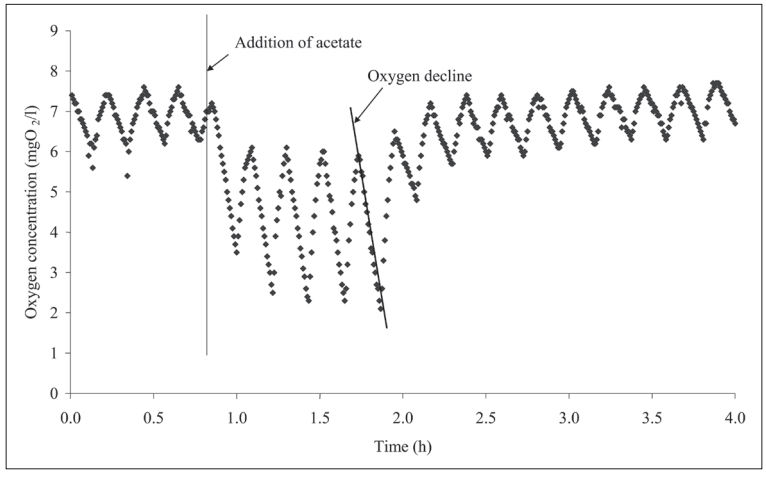


Figure 2. *A plot of the oxygen concentration during intermittent aeration of activated sludge from Källby WWTP in Lund. Acetate added after 0.8h.*

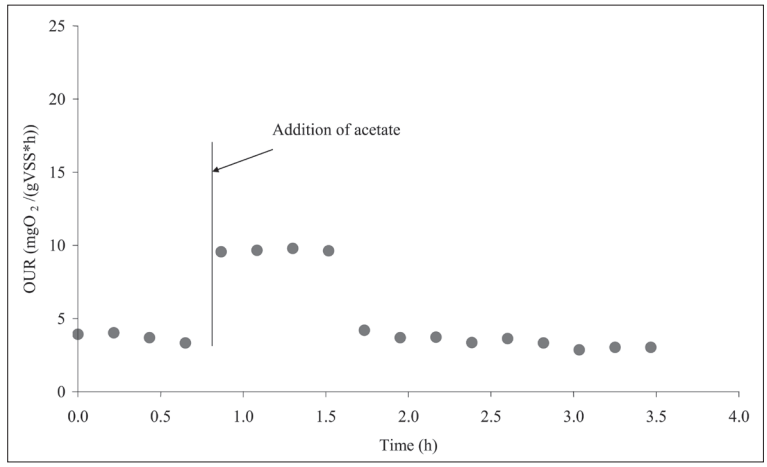


Figure 3. *Oxygen uptake rate graph/ respirogram corresponding to the plot of oxygen concentration in Figure 2 for activated sludge from Källby WWTP in Lund.*

shows a typical respirogram for municipal activated sludge with an addition of acetate. The oxygen uptake rate measured before the addition of acetate is due to the endogenous respiration of the activated sludge. The endogenous respiration is often defined as the oxygen consumption of microorganisms in the absence of substrate, but many mechanisms and processes are included in the conception of endogenous respiration. Van Loosdrecht and Henze (1999) have described the phenomena in more detail and also tried to organize the mechanisms and processes involved in microbial endogenous respiration. When easily biodegradable carbon source is added to activated sludge, the OUR will increase and when the carbon source is consumed, the OUR will return to about its initial level. The more easily degradable a carbon source is, the higher the OUR becomes, until it reaches its maximum for the activated sludge.The maximum uptake rate is reached when all bacteria capable of utilising the organics grow at maximal speed.

If a mixture of organic material is added to activated sludge, such as wastewater, the OUR curve will in principle get the shape of the one shown in Figure 4, according to Kristensen *et al.,* (1991). The highest peak represents the directly biodegradable substances while the next level indicates a more slowly degradable material and so on further down to the endogenous respiration rate. Normally OUR curves or respirograms for mixtures of carbon sources are not as distinct as the one in Figure 4, but still similar pattern can be followed.

Recent studies by Hagman *et al.,* (2006) has shown that a mixture of easily biodegradable carbon sources results in a higher OUR peak approximately corresponding to the sum of the two individual carbon sources in the mixture. This phenomena is only detectable when identical experiments are performed with the same activated sludge and additions of single and mixed substrate respectively are tested.

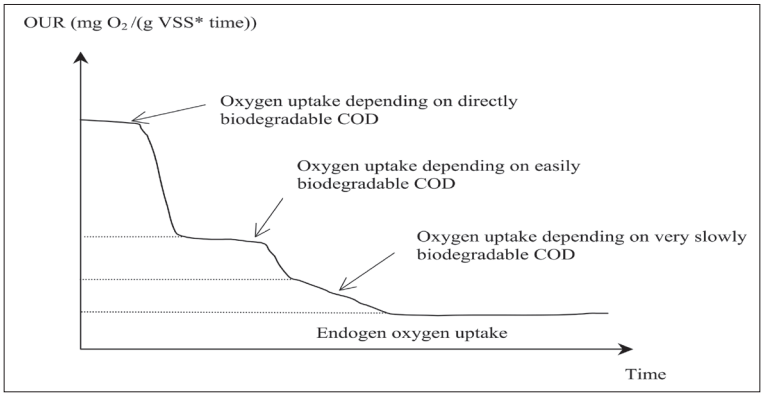


Figure 4. *Typical development of the respiration rate as a function of time for a mixture of carbon sources according to Kristensen et al., (1991).*

## Experimental conditions

The specific OUR depends on many factors and the most important are mentioned below.

*Carbon source*

The OUR varies with the type of organic substrate available and therefore it is important to use the same substrate when comparing the capacity of different activated sludges. Acetate is often used as reference substrate since it is known to be a very easily degradable organic matter for heterotrophic bacteria.

*pH*

The aerobic degradation of organic matter is depending on a pH between 6 and 9. Since $CO_2$ is produced during oxygen respiration, the pH will slightly increase and no adjustments for stabalising the pH is normally needed.

*Nitrification inhibitor*

When sludge from a nitrifying treatment plant is used some of the oxygen consumption depends on the oxygen used for nitrification instead of oxidation of organic matter. To avoid nitrification during measurements of organic degradation, a nitrifying inhibitor is used. Often allylthiourea (ATU) is applied for this purpose. It inhibits the conversion of ammonia to nitrite. For OUR tests levels of 12mg/l is typically found to be used. However, investigations have shown that additions of 10mg/l of ATU impacts the endogenous respiration of the sludge, which results in a lowered OUR (Benes *et al.*, 2002). Therefore one should be aware of how the results are used depending on the application of the method.

*Temperature*

The oxygen uptake rate is also dependent on the temperature and generally the activity increases with the temperature (Roš, 1993 and Henze *et al.*, 2002). For that reason it is important to keep the temperature constant during the entire experiment. Laboratory experiments are often performed at 20°C, but in some cases it is preferable to keep the same temperature in the experiment as in the real plant. This is especially important when applications of the results are used for operational control and for process modelling of a plant operated at a temperature different from 20°C.

## Equipment

There are many types of equipment available on the market, more or less advanced. Spanjers *et al.*, (1998) describes various possible measuring techniques and their suitability depending on the application purpose of the survey. In this study the method used is based on oxygen measurements in the liquid phase and the oxygen variations are followed directly in the reactor by electrochemical sensors. In order to make a series of experiments the biomass has to be re-aerated. The re-aeration could though be avoided if the biomass continuously were aerated and samples were taken out to a separate container during the OUR measurements, but it demands a slightly more complicated equipment compared to the one used in this study. In addition, comparisons between the two methods showed almost no difference in the results obtained (Hagman, 2003).

The laboratory set-up used in this study is shown in Figure 5. It consists of a batch reactor with stirring placed in a water bath to ensure constant temperature. The aeration is controlled by a timer and an oxymeter (WTW Oxi 197-S and/or WTW Oxi 196) is placed in the cover of the reactor for continuous measurements of the oxygen concentration.

## Experimental procedure

The procedure of the oxygen uptake rate experiments performed in this study is similar to the one described by Kristensen *et al.*, (1991). The activated sludge is sam-

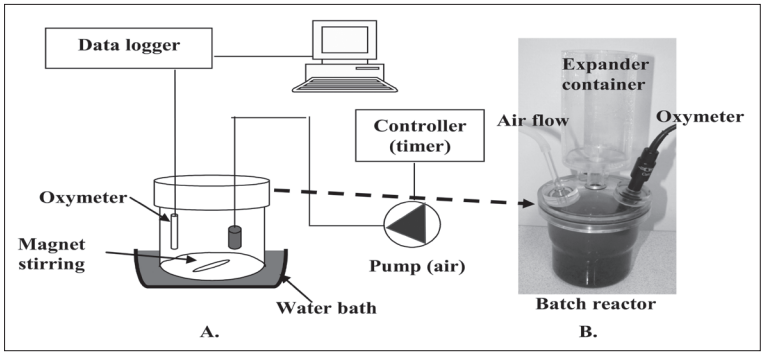


Figure 5.
A. *Schematic picture of the laboratory set-up for OUR-measurements.*
B. *Laboratory batch reactor 1 litre.*

pled at the treatment plant and directly transported to the laboratory. It is temperated and aerated for about 30 minutes in order to degrade any organic matter produced as a result of hydrolysis in the sludge during transport. It is followed by determination of SS, VSS and pH. Before the test is started, nutrients and ATU ($NH_4$ $2SO_4$ 0.236g/l, $KH2PO_4$ 0.044g/l and ATU 12 mg/l) is added. The decline in oxygen concentration is followed during a period without aeration, typically 5–10 minutes depending on sludge concentration and level of activity. For series of measurements the sludge is re-aerated and when the sludge has reached the oxygen saturation level another OUR can be measured. The carbon source or wastewater that is to be tested can then be added, for good mixing of the added substrate it is introduced to the reactor during aeration.

## Application of oxygen respiration measurements

The respirometry test is nowadays well established and widely used for both research and at wastewater treatment plants, but interpretation of the results still provokes discussions among researchers. Below, the most common applications of the method is presented.

### Wastewater characterisation

OUR measurements can be used for characterization of wastewater streams, both batch tests and on line respirometry are reported to be used for this purpose (Kristensen *et al.,* 1992 and Kristensen *et al.,* 1998). Wastewater treatment plants receive concentrated wastewater streams originating from several sources both internal and external. Examples of such streams can be mixed municipal wastewater, concentrated organic streams from industries and internal recirculation streams from different parts of the treatment plant. Here follows some of the common applications of OUR tests for characterisation of wastewater.

*Variations in organic load/treatability*

There are always variations of the organic load in the incoming wastewater due to industrial contributions and its production circle, day of the week and changes of numbers of inhabitants for example during holidays. Information about the organic load of the incoming wastewater to a treatment plant helps the operator to control and manage the plant in a more optimal manner. Xu and Hasselblad (1996) have proposed a simple biological method to estimate the readily biodegradable COD in wastewater based on single OUR tests, which can be used for estimation of the biodegradable organic fraction in the wastewater.

Since wastewater treatment plants often receives wastewater from different sources within various flow rates and waste concentrations, it is of high interest to get knowledge about the biological treatability of the separate streams. Industrial wastewater streams vary "a lot" depending on the production processes involved at the industry. OUR tests are described to be used for characterization of industrial wastewater by Orupõld *et al.,* (1999). On line respirometry is getting implemented at wastewater treatment plants for continuous measurements. It is used as forward treatment strategy as well as for plant performance control (Witteborg *et al.*, 1996).

*Toxicity and inhibition*

OUR measurements can also be used as a toxicity test and for detection of inhibitory streams (Ko *et al.*, 2002 and Le Bonté *et al.*, 2005). Figure 6 demonstrates the effect of adding a toxic water to activated sludge. Acetate additions result in a rapid increase in the OUR while the biological treated leachate water only show a smaller increase when introduced to the activated sludge. The toxic wastewater on the other hand results in a decrease in the OUR compared to the endogenous respiration level, which indicate a decay or inhibition of the microorgaisms in the sludge. Respirometry tests for toxicity detection is very useful since results are received quickly, but for a more quantitative description of the toxic effect it is preferably used in combination with $EC_{50}$ measurements ($EC_{50}$ represents the concentration of a com-

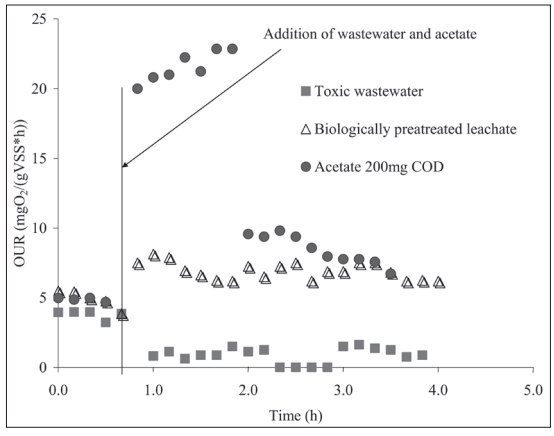


Figure 6. *Toxicity test. Three parallel respiration tests, one with additions of acetate, one with biological pre-treated leachate and one with toxic wastewater. Sludge from the same plant with identically conditions was used in all reactors.*

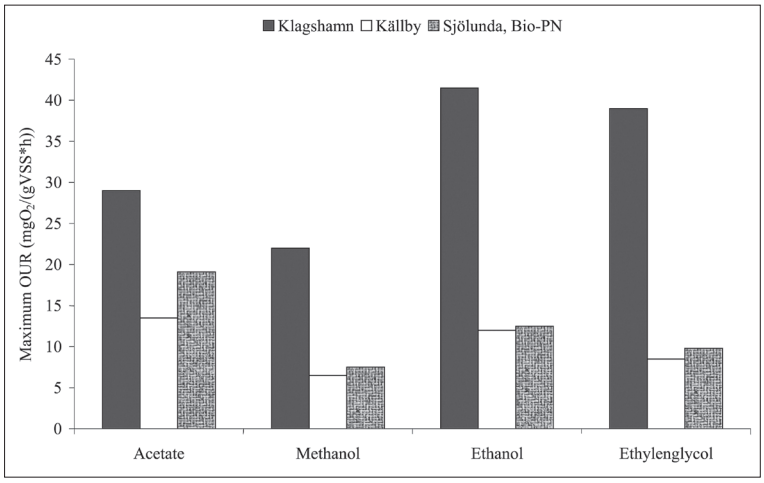


Figure 7. *Oxygen uptake rates were measured in sludge from three municipal wastewater treatment plants, while additions of acetate, methanol, ethanol and ethylenglycol respectively were added as carbon source.*

pound where 50 % of its maximal effect on the tested organism is observed). Substances that only are slightly inhibitory are less easy to detect since comparisons have to be done with previous measurement on the same sludge. It is therefore important to make continuous respiration tests at the same spot at the plant in order to be able to detect changes.

## Activated sludge characterization

*Process performance*

Activated sludge from different plants hold various capacity for degradation of organic matter since the sludge composition is the result of the exposure of the wastewater entering the particular plant. Figure 7 shows an example of how the maximum OUR can vary for the same organic substrate from one activated sludge to another. It emphasises the importance in following the sludge capacity of the same sludge over the time, in order to recognise changes in the process performance and to predict future treatment results. Information concerning sludge characteristics is a prerequisite of stability control and plant optimization.

*Activated sludge changes*

By regular OUR tests at different places at the plant it is possible to follow changes in the process performance. Figure 8 shows an example of detection of activated sludge capacity changes during a period of exchange of carbon source at a wastewater treatment plant. The maximum specific OUR for acetate increased over time after acetate addition instead of glucose and an adaptation to the actual carbon source was seen. Similar variations depending on, for example wastewater characteristics,

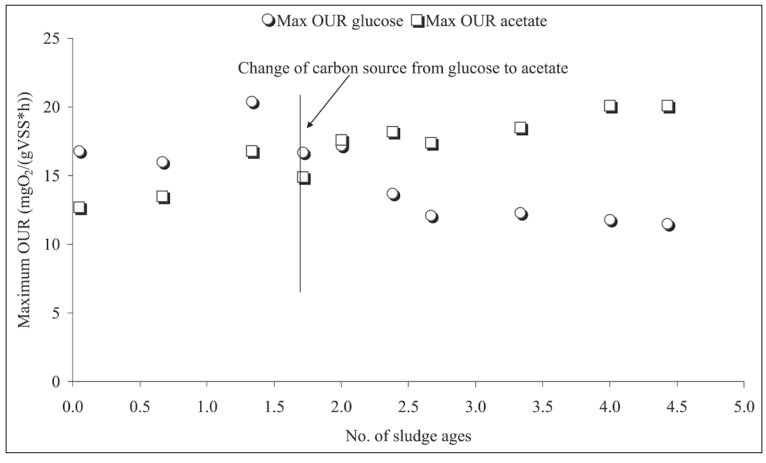


Figure 8. *Maximum oxygen uptake rates for acetate and glucose were followed in activated sludge exposed to glucose in the first period and acetate in the second period (Hagman, 2003).*

process failures or process changes can be followed if continuous measurements are performed at the same place at the plant. It will allow the plant operator to use OUR measurements for fast trouble shooting.

## Combinations with other methods

In order to obtain and extract more detailed information about the microbiology of the activated sludge, supplementary methods and analysis of the sludge and wastewater have to be applied. For further information about the ecology of the microorganisms, microbiological methods such as visually microscopy studies and various staining procedures can be used. The most well known manual for microscopy studies of activated sludge is written by Jenkins *et al.*, (1993) and Eikelboom (2000).

By fluorescence in situ hybridisation (FISH) analysis, it is possible to identify a specific microorganism group or species in an environment of mixed cultures of microorganisms, without cultivation. The procedure for performing FISH experiments demands special training and equipment and in combination with the high experimental costs the method gets less available. In order to investigate the microbial preferences for specific substrate and the capability of utilising a substrate, microautoradiography (MAR) is a method that can be used. MAR is a technique which enables a direct visualisation of the active biomass and their metabolic capabilities without cultivation. It gives the possibility to investigate the ecological functions of a mixed biomass like activated sludge or biofilm as well as individual cell activity. The method is complicated and only experienced experts are able to reproduce reliable results, it is not usable as a routine analysis.

## Final reflections

OUR measurements and respirometry have demonstrated to be a useful tool at wastewater treatment plants in many aspects. The measurements can be performed using simple equipment, although more advanced and expensive equipment is available on the market. Compared to many other methods it is relatively easy to apply and the data could be used for simpler characterisation and process control as well as for more complex tasks like simulation and plant design. Both batch tests and on-line measurements are possible depending on purpose of application. For extended information of the activated sludge the OUR test can preferably be combined with other methods.


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