20 COMPARISON OF TWO RESPIROMETRIC PRINCIPLES FOR THE DETERMINATION OF SHORT-TERM BIOCHEMICAL OXYGEN DEMAND

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INTRODUCTION

Current legislation of effluent discharges from wastewater treatment plants is geared to enforce a constant low level of pollutant discharged, independent of seasonal variations of the capacity of the receiving body or variations in wastewater load that enters a treatment plant. While some discussion has been incited for a long time now[1] whether this policy should be maintained, it must be stressed that the central goal of a treatment plant will always be to guarantee a certain effluent quality under time-varying influent compositions.

When one considers the variation in the effluent concentration, a treatment plant can be regarded as a lowpass filter where high frequency disturbances are dampened.[2] However, this does not hold for the required treatment capacity that must follow the changes in incoming load closely to guarantee stable effluent quality. From a process control and economic perspective it is therefore required that the process conditions in which the biocatalysts perform their task are set to adjust to these varying requirements. Feedback control of certain variables is a traditional approach, e.g. dissolved oxygen control.[3] However, certain process time constants are so large that the delay between initiation of a control action and its effect on the plant may be prohibitively long to make feedback control successful.[4] As an alternative for such systems feedforward control has been proposed.[3,5] However, it is well-known that this type of control is sensitive to the quality of the process model.[6] Evidently it is essential to measure the disturbance that is considered important from a control point of view.[4, 5]

In this paper the measurement of probably the main disturbance variable of a wastewater treatment plant is considered, i.e. the wastewater concentration. Chemical methods such as on-line COD and TOC monitors that have been proposed for long[3] to quantify the concentration of pollutants in influents suffer from several drawbacks.[7] Next to the problems associated with vulnerability of the devices and the concomitant high maintenance requirements, the major flaw is that these methods cannot give any information on the treatability of the pollutants. On the other hand, it must be stressed that these methods can provide the data at a high frequency. Traditional methods that rely on the monitoring of the biodegradation of the pollutants to obtain an indication of the treatability such as the BOD_5^{20}-method are clearly inapt to provide the necessary information for feedforward process control due to the large time delay between sample introduction and measurement result. However, the principle of monitoring the oxygen uptake for assessment of the treatability and pollutant concentration of a wastewater is a very powerful one, because most wastewater treatment processes rely on aerobic degradation of the waste. Therefore, methods have been proposed to decrease the response time of these biologically medicated methods to such a level that application of the sensor data within control loops becomes feasible.

In this contribution two such—independently developed—respirometric principles for the assessment of the variations in influent concentration are presented and experimentally compared. Complemented with flow rate information it will be illustrated with some case studies that interesting feedforward control strategies can be devised with this information.

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PRINCIPLES

In this section the basics of the two respirometric principles that are evaluated further are presented. The different approaches to calculate the BOD_{st} of the samples are illustrated with simulated raw data.

General

The short-term Biochemical Oxygen Demand, BOD_{st} is defined as the amount of oxygen consumed for biodegradation of readily biodegradable pollutants per volume of wastewater. In tradition respirometric determination of wastewater pollutant concentration small amounts of biomass are mixed with a large wastewater sample (typically S_0/X_0 is between 10 and 100 mg BOD_5[20]/mg MLVSS). As a result, important growth is required before the available pollutants are degraded and possibly a lag phase may occur where adaptation of the sludge to the pollutants takes place. Standardized procedures have been prescribed.[8] Important for the discussion of the BOD_{st} methods is that normal procedure imposes the addition of a nitrification inhibitor to the sample to measure only heterotrophic oxygen consumption. This is not true for the BOD_{st} methods. Consequently, it can be anticipated that part of the BOD_{st} is due to nitrification oxygen demand.

To speed up their response time, the techniques for BOD_{st} determination are based on a low S_0/X_0 ratio (typically 1/200). These conditions are obtained by addition of a small aliquot of wastewater to activated sludge mixed liquor present in the test vessel. Therefore, the degradation time can be reduced considerably (often less than 30 minutes) while no change in the concentration of the activated sludge is to be expected.[9] Because of this short experimentation time, it is also evident that some pollutants in the wastewater sample will not be degraded, i.e., only the readily biodegradable fraction is measured.

Due to the increased respiration resulting from the high degradative capacity available in the test vessel, problems may arise to suffice the oxygen requirements of the sludge. Respirometric methods that are based on measurement of the decrease of the initial amount of oxygen present in the mixed liquor e.g.,[10,11] are severely restricted because of the danger for oxygen limitation. As a result the dynamic concentration range of such methods is small, with maximum sample additions of 5 mg BOD_{st}/L mixed liquor. Naturally, aeration of the sludge, as in the two methods presented below, solves this problem.

In a similar way to the conventional methods, the consumption of oxygen is monitored either volumetrically using pressure transducers and CO_2 stripping[12] or by specific oxygen sensing devices, either in the liquid phase, i.e. dissolved oxygen (DO) probes, or in the gas phase using fuel cells[13] or paramagnetic oxygen analyzers.[14] Clearly most respirometric methods that have been proposed rely on DO probes to monitor oxygen uptake.

Hardware

The configuration of both respirometric principles evaluated in this study is schematized in Figures 1 and 2. In the first setup, a single vessel is used in which activated sludge from the treatment plant is brought into contact with wastewater samples. In the hardware implementation of this measuring principle as used in this study (RODTOX, Kelma bvba, Niel, Belgium), the volume of this vessel is

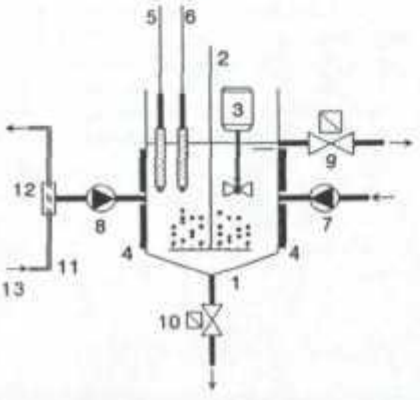

Figure 1. Hardware one-vessel respirometric principle. (1) test vessel; (2) aerator; (3) mixer; (4) heating element; (5) pH probe; (6) DO probe; (7) calibration mixture addition pump; (8) wastewater sample addition pump; (9) decantation valve; (10) sludge withdrawal valve; (11) fast loop; (12) cross-flow filter; (13) wastewater.

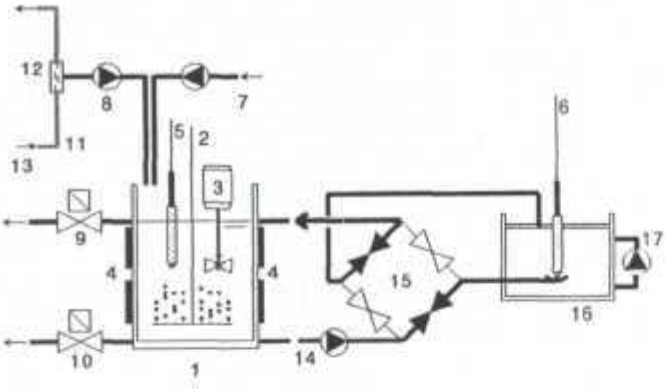

Figure 2. Hardware two-vessel respirometric principle. For items 1–13, see caption of Figure 1. (14) sludge recycle pump; (15) solenoid valves for flow switching; (16) respiration chamber; (17) mixing pump.

10 L. A heating element maintains the mixed liquor temperature at the desired value, typically (and also in this study) at 25 ± 0.1°C.

Maintaining a constant temperature is important for proper estimation of the BOD_{st}. Optionally, a pH control unit can be installed in case danger exists that the condition of the sludge is affected by pH changes caused by either sample concentration or metabolic activity. In this study, pH was maintained at 7.5 ± 0.1. The central part of this respirometer is the DO probe. Continuous supply of oxygen is provided to accommodate the oxygen demand of the activated sludge and keep the dissolved oxygen concentration above 2 mg O_2/L. Two sample pumps can be started to inject either a sample of a calibration mixture with known concentration or a wastewater sample that is obtained from a cross-flow filter (0.5 mm pore size) installed in a fast loop from the influent line. Sludge can be withdrawn from the bottom of the test vessel. Since samples are added to the vessel, decantation of supernatant after a settling period is required to maintain the volume of the mixed liquor within reasonable limits. Note that this hardware configuration will be denoted further as the one-vessel principle.

In the hardware implementation of the other principle studied (denoted further two-vessel principle) (RA1000, Manotherm bv, Rotterdam, The Netherlands), two vessels are used in the experimental setup (Figure 2). In the first aerated vessel (in the current investigation a 2 liter vessel), many similar components as in the one-vessel principle can be recognized, i.e., temperature and pH control units, an aerator, two sample addition pumps, decantation and sludge withdrawal provisions. The monitoring of the biological oxygen consumption, while being based on one and the same DO probe, is done in a separate unit, the unaerated respiration chamber (with a volume of 0.75 L). Here lies the main difference with the one-vessel principle. In the respiration chamber the oxygen uptake rate of the activated sludge is obtained by measuring the decrease in dissolved oxygen as the result of the retention in the chamber for a mean hydraulic retention time of typically 2 minutes. To be able to monitor this DO decrease with only one probe—to reduce complexity and danger of changing probe sensitivities (causing large errors when small differences between the two signals exits)—a configuration was developed in which a single DO probe measures the dissolved oxygen concentration in both the inlet and the outlet flows of the respiration chamber. To achieve this a four-value system is installed which changes the flow direction through the chamber with a specified frequency, typically twice per minute. The frequency of flow switching is limited by the response time of the DO probe.

Raw Data

Dissolved oxygen readings typically obtained upon sample injection to the activated sludge in the aerated test vessels are given in Figures 3a and 4a, respectively. In the one-vessel principle the introduction of wastewater to endogenously respiring activated sludge results in an increased oxygen uptake rate that disturbs the steady state dissolved oxygen concentration. After some time, biodegradation of pollutants is completed and DO returns to the steady state level C_s as the result of continuous aeration. The DO mass balance on which the BOD_{st} determination will be based is:

$$\frac{dC}{dt} = K_L a\,(C_s - C) - OUR_{ex} - OUR_{end} \qquad (1)$$

where the volumetric mass transfer coefficient, $K_L a$ and the saturation dissolved oxygen concentration, C_s, determine the oxygen supply rate. On the other hand, oxygen is removed from the mixed

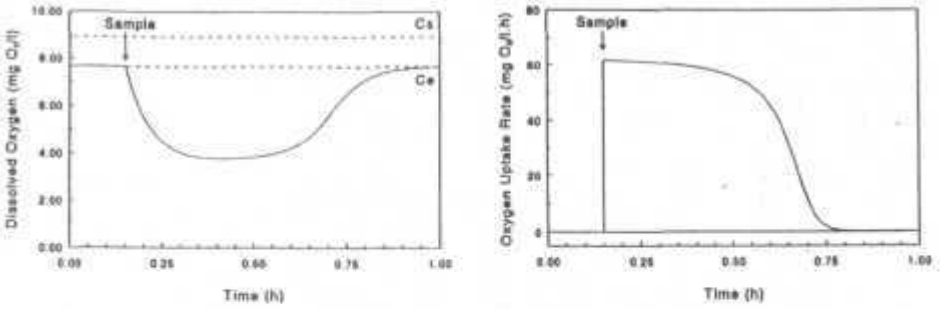

Figure 3. Raw data one-vessel principle: (a) Dissolved oxygen, (b) OUR_{ex}.

liquor due to uptake for endogenous (OUR_{end}) and exogenous respiration (OUR_{ex}). The steady state dissolved oxygen level C_e is determined by the endogenous respiration only and can be deduced from mass balance Equation 1 at steady state:

$$C_e = C_s - \frac{OUR_{end}}{K_L a} \tag{2}$$

Substituting OUR_{end} from Equation 2 into Equation 1 results in the dissolved oxygen mass balance which will be used below:

$$\frac{dC}{dt} = K_L a\,(C_e - C) - OUR_{ex} \tag{3}$$

Since the OUR_{ex} time course is central to the estimation of BOD_u, one must be capable of calculating this from Equation 3. Because C_e and C in Equation 3 are measured or can be derived easily from the DO readings (dC/dt), the only unknown left in Equation 3 is the $K_L a$ which must be estimated from the raw data. Vanrolleghem[15] developed methods to estimate $K_L a$ from the DO profiles obtained, based on the reaeration which occurs after biologically induced depletion of the oxygen in the test vessel. Figure 3B shows the OUR_{ex} data calculated from the raw DO output of Figure 3a.

In the two-vessel principle, raw dissolved oxygen data as depicted in Figure 4a are obtained. The oscillation is induced by the fact that the electrode is subjected for a short period (typically 30 seconds) to the dissolved oxygen concentration at the inlet of the respiration chamber and subsequently to the outlet DO (which is lower as the result of biological oxygen consumption). Due to the sluggish response of the probe (with a typical first order time constant of 10 seconds), a smooth transition from the inlet to the outlet DO is obtained instead of the expected bang-bang type probe output.[16]

For a good understanding of the longer term DO evolution, the following mass balances must be kept in mind. Dissolved oxygen in the first vessel is governed by oxygen supply through aeration and

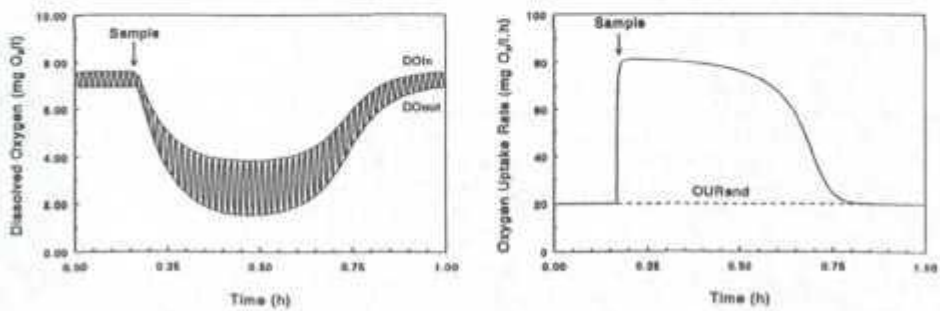

Figure 4. Raw data two-vessel principle: (a) dissolved oxygen at inlet and outlet of respiration chamber, and (b) $OUR = OUR_{end} + OUR_{ex}$.

biological oxygen uptake – as described in Equation 1 – but also by a mixed liquor flow F to and from the respiration chamber:

$$\frac{dC}{dt} = K_L a\,(C_s - C) - OUR_{ex} - OUR_{end} + \frac{F}{V}(C_{rc} - C) \tag{4}$$

where V represents the volume of the test vessel and C_{rc} the dissolved oxygen concentration in the respiration chamber. The evolution of the latter concentration is described by the following mass balance over the respiration chamber:

$$\frac{dC_{rc}}{dt} = \frac{F}{V_{rc}}(C - C_{rc}) - OUR_{end} - OUR_{ex} \tag{5}$$

where V_{rc} stands for the volume of the respiration chamber. The dissolved oxygen concentrations measured by the DO probe at inlet and outlet of the respiration chamber are therefore determined by the set of differential Equations 4-5 that must be solved simultaneously. However, since one is primarily interested in the biological oxygen uptake process for pollutant degradation, one must only focus on the solution of the mass balance of the respiration chamber to obtain the respiration rate (OUR_{ex} + OUR_{end}). This will be used subsequently for BOD_{st} determination. Figure 4b shows the total OUR corresponding to the DO data set of Figure 4A. One easily recognizes the constant OUR_{end} level.

Note that the mass balance Equation 4 predicts that the dissolved oxygen time profiles measured at the inlet of the respiration chamber highly resembles the DO profile of the one-vessel principle. This is also evident from the raw data depicted in Figures 3a and 4a. Thus, the interpretation of the one-vessel principle could also be applied (after some minor modifications) to the two-vessel based measurements.

BOD_{st} Determination

The BOD_{st} is the amount of oxygen consumed for biodegradation of pollutants, or in mathematical terms:

$$BOD_{st} = \int_0^{tfin} OUR_{ex}(t)\mathrm{d}t \tag{6}$$

This *tfin* is defined as the time needed to return to the endogenous respiration rate after sample injection.

The BOD_{st} in case of the one-vessel principle can be obtained by integration over the DO profile (with a length of *tfin* minutes), i.e.,

$$\int_0^{tfin} dC = \int_0^{tfin} K_L a\,(C_s - C(t))dt - \int_0^{tfin} OUR_{ex}(t)\mathrm{d}t \tag{7}$$

Since $K_L a$ can be assumed constant within this short time interval:

$$C(0) - C(tfin) = K_L a \int_0^{tfin} (C_s - C(t))dt - \int_0^{tfin} OUR_{ex}(t)dt \tag{8}$$

Because the dissolved oxygen concentration at the beginning and the end of a BOD_{st} determination are the same, and the latter integral of Equation 8 is, by definition (Equation 6), equal to the BOD_{st}, one can write:

$$BOD_{st}^{vessel} = K_L a \int_0^{tfin} (C_s - C(t))dt \tag{9}$$

In other words, the BOD_{st}^{vessel} is equal to the area of the dissolved oxygen profile multiplied by a constant, the volumetric mass transfer coefficient.

To eliminate problems associated with the determination of $K_L a$, one may take advantage of a calibration mixture (with a known concentration) to relate the waste concentration in an unknown with the calibration waste content:

$$BOD_{st}^{x} = \frac{A^{x}}{A^{Cal}} \cdot BOD_{st}^{Cal} \tag{10}$$

where A^x and A^{Cal} are the integrals of the DO profiles of the unknown and calibration sample respectively. In this way $K_L a$ has been eliminated from the calculations. One must keep in mind, however, that $K_L a$ changes may affect the BOD_{st} determinations. These changes are, however, rare and can be anticipated by regular injection of the calibration mixture. In the implementation of this principle, this is typically done every 2 to 4 hours because these calibrations form the basis of the toxicity detection principle included in this implementation.[17] However, in this paper, this approach was not followed, i.e., all BOD_{st} determinations reported were obtained from Equation 9.

Evidently, the BOD_{st} of the injected sample is deduced from:

$$BOD_{st}^{Sample} = \frac{V_{sample}}{V_{vessel}} \cdot BOD_{st}^{Vessel} \tag{11}$$

In the two-vessel approach, the calculations are even more straightfoward. Here, the definition[6] can be applied immediately, although one must subtract the endogenous respiration OUR_{end} from the measured total respiration rate to obtain the exogenous oxygen uptake rate OUR_{ex}. Taking the integral then gives the short-term BOD of the injected sample.

The respirometric methods with built-in oxygen supply have an inherently large dynamic range of, typically, 5 to 100 mg BOD_{st} supplied per liter activated sludge in the test vessel. Injections of a volume of wastewater that results in such additions allow reliable BOD_{st} determinations. This amount of pollutants can be present in different sample volumes, depending on the pollutant concentration of the sample. In the hardware implementations, it is possible to automatically adjust the injected volume of sample. For instance, with the precision membrane pumps installed in the one-vessel implementation used in this study, a volumetric range of 2 to 500 mL can be applied to the 10 liter test vessel. Consequently, the range of sample waste concentrations that can be assessed increases considerably. Finally, Vanrolleghem et al.[18] showed that manipulation of the mass transfer efficiency in the aerated test vessel can increase the measurable concentration range with another factor 10. An overall concentration range between 10 and 500000 mg BOD_{st}/L wastewater is achieved in these sensors.

RESULTS

A study was set up to compare both principles for the determination of the BOD_{st}. In this investigation, both respirometers were brought to the same site and experiments were done with identical sludge sources and identical wastewater samples for both principles. To prevent errors due to sample pumping (in this way ensuring that the fundamentals are compared), all sample additions were done manually using graduated cylinders. It was checked whether temperature and pH levels were identical for both setups.

The sludge and wastewater sources used in the evaluation were the following. Sludge and wastewater were sampled at the municipal wastewater treatment plant of Bennekom (the Netherlands). A treatment works with a large industrial input was also included, i.e. the Ossemeersen (Gent, Belgium). Finally, a facility was considered that predominantly treats hospital wastewater, the Maria Middelares plant, also at Gent. All plants are nitrifying, although the Ossemeersen plant only partially. For each plant sludge and presettled influent was collected and stored, for a max. of 2 days at 4°C, before use. Care was taken that sludges and wastewaters were applied at identical time instants to preclude any effect due to a difference in storage conditions. Each activated sludge type was used during one day and was supplied with wastewater samples from the three sources. Three injections of different volumes were done for each wastewater. The sequence of application and the amounts injected per volume of sludge were identical for both principles tested, to eliminate effects due to the history of the sludge.

Raw Data

Typical raw data collected with the injection of Bennekom wastewater to Ossemeersen sludge are given in Figures 5 and 6, for the one-vessel and two-vessel principle respectively. One observes the high resemblance between both OUR data sets.

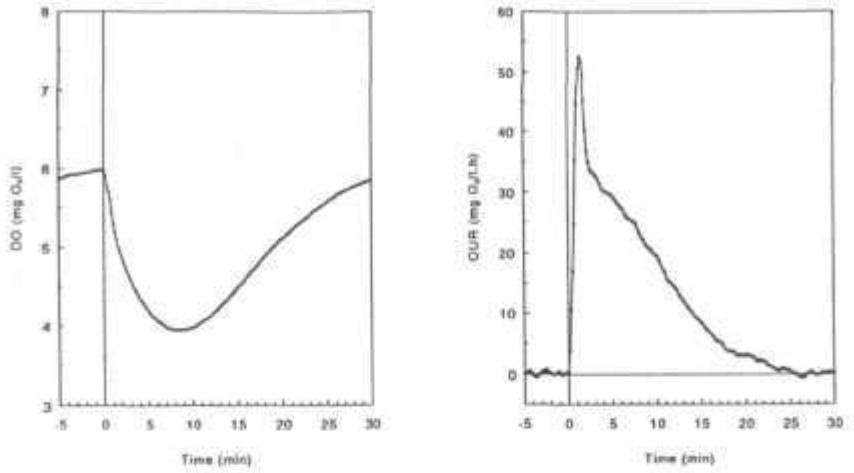

Figure 5. One-vessel principle: DO (left) and OUR_{ex}-profiles (right) for an injection of Bennekom wastewater to Ossemeersen sludge.

The mean BOD_{st} and the standard deviation obtained from the three injections for each combination of wastewater and sludge are summarized in Table I. These data have been used in the statistical analysis presented in Table II. At this stage note that the multiple factor analysis of variance provides an estimate of the measuring error which is found to be lower than 10 mg BOD_{st}/L, corresponding with a relative measuring error of 5%. Such low measuring errors will allow one to make sensitive evaluations of different effects to which the measurement is subjected.

The wet analysis of the wastewater samples is also included in Table I. One observes the high solids content of all samples, especially the Ossemeersen influent.

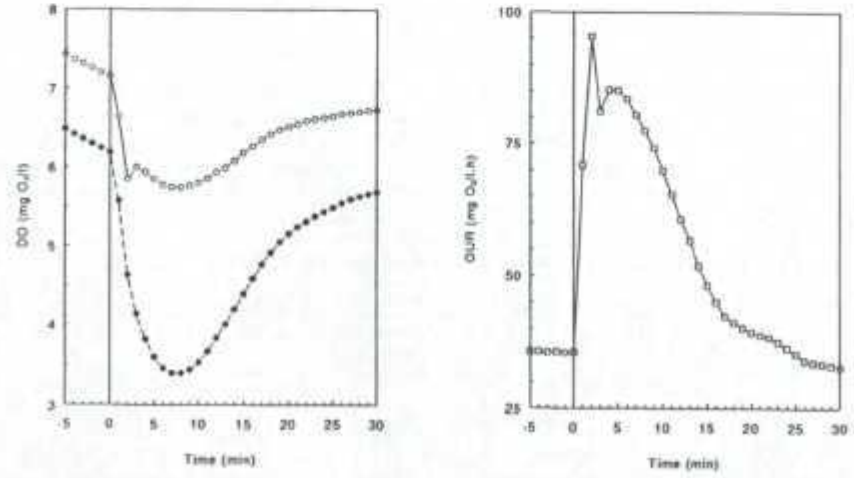

Figure 6. Two-vessel principle: DO in and DO out of the respiration chamber (left) and OUR-profiles (right) for an injection of BENNEKOM wastewater to Ossemeersen sludge (DO + OUR).

Table I. BOD_{st} and Other Wastewater Characteristics for the 3 Types of Wastewaters Tested. BOD_{st} Concentrations Are Given as the Mean Value ± Standard Deviation for Both Respirometric Principles and Respective Sludge Types

Sensor Principle	Sludge Source	Wastewater		
		Be	MM	Os
One vessel	Be	318 ± 10	146 ± 5	83 ± 2
Two vessel		296 ± 14	131 ± 7	58 ± 3
One vessel	MM	321 ± 9	158 ± 5	76 ± 3
Two vessel		306 ± 5	126 ± 8	65 ± 1
One vessel	Os	341 ± 9	185 ± 9	75 ± 2
Two vessel		329 ± 11	147 ± 12	63 ± 3
BOD_5		118	211	165
COD		455	650	715
COD(.45)[a]		232	312	98
KjN		87	39	38
NH_4-N		77	30	24
SS		187	317	633

[a]COD(.45) is the COD content of a sample after filtration with a .45 μm membrane filter.

Comparison of Both Principles

Analysis of Table I shows that both measuring principles give roughly the same BOD_{st} of the wastewaters. The difference found between the two principles is, however, highly significant (Table II). Several possible causes for this deviation were considered. First, a thorough check was made on the experimental conditions and the volumes of sludge and wastewater applied. A second possibility is that the DO probes were not calibrated exactly in the same way. Indeed, the slope of the DO calibration has a direct effect on the calculated BOD_{st}. Note that a wrong intercept of the DO probe calibration has no effect because in the calculations only differences between DO readings are used. A third potential reason for the difference in BOD_{st} estimates is that a difference in mass transfer characteristics in the aerated vessels of both principles leads to a difference in stripped pollutants which, subsequently, would result in a difference in BOD_{st}. A systematic error in the estimation of the K_La in the one-vessel principle may also be at the basis of the discrepancy. Note that BOD_{st} estimation using the calibration mixture approach (Equation 10) solves this problem. Another possible cause that was considered is the difference in sampling frequency in both principles. However, some calculations showed that its effect, though in the same direction (lower BOD_{st} for lower sampling frequencies), was not sufficient to account for the observed difference. Finally, because each respirometer was operated separately by one and the same person during the experiments, it is evident that the experiment was not completely randomized. This might have resulted in the observed difference.

It is concluded that some further study is required in which attention is focused on these issues, especially the DO meter calibration, the K_La estimation and the randomization of the experiment. Another possibility would be to reevaluate the available raw DO data obtained at the inlet of the respiration chamber according to the one-vessel principle after a slight modification of the mass balance with a flow term to the respiration chamber (Equation 4). Overall, however, one should take

Table II. Multiple Factor ANOVA of the Collected BOD_{st} Data Set

Factor	SumSquar	df	Variance	F-value	$F_{0.95}$	$F_{0.99}$	Level
Apparatus	5460.2	1	5460.2	63.6	4.13	7.42	**
Sludge	3287.1	2	1643.6	19.1	3.29	5.28	**
Water	580643.6	2	290321.8	3380.2	3.29	5.28	**
Interaction A×S	10.1	2	5.1	0.1	3.29	5.28	
Interaction A×W	494.3	2	247.2	2.9	3.29	5.28	
Interaction S×W	1889.7	4	447.5	4.8	2.65	3.9	**
Interaction A×S×WS	673.9	4	168.5	2.0	2.65	3.9	
Error	3092.0	36	85.9				
SSTOT	595550.9	53					

into account that the comparison of respirometric principles has been very sensitive, in view of the very low measuring error which allows that effects of about 10% can be extracted from the experimental data.

From the standard deviations reported in Table I, it can be deduced that for the experiments presented here, the two-vessel principle is slightly less precise than the one-vessel principle. A possible cause may be the lower measuring frequency (10 seconds vs. 1 minute sampling period), and the concomitantly smaller OUR_{ex} data set (typically 20 versus 120 OUR_{ex} data points, see Figure 5 and 6). Also, one observes a slight tendency of errors being proportional to the measured BOD_{st} level.

Influence of Sludge Type

It was expected that adaptation of sludge to a wastewater would lead to a higher biodegradability of the pollutants present in an influent taken at the same works as the sludge is taken from. This would mean that the BOD_{st} contents of the diagonal in Table I would be significantly higher than the other estimates. No such effect can be observed. Rather, one observes that the Ossemeersen sludge degraded more pollutants in the Bennekom and Maria Middelares wastewater than their respective sludge, while in the case of the Ossemeersen wastewater, all sludges degrade the same amount of pollutants. The Maria Middelares and Bennekom sludges possess similar degradative capacities.

Table II also suggests an interaction effect between the factors wastewater and activated sludge (AxW); i.e. the effect of the factor activated sludge on the BOD_{st} is not constant but depends on the factor wastewater. This is exactly as discussed above.

Comparison with Traditional Methods

The data summarized in Table I allow one to deduce that the BOD_{st} does not correlate with the BOD_5 content of wastewaters. This has been observed before. It is particularly because nitrification oxygen demand is not included in the BOD_5 method while being included in the BOD_{st} determination. Indeed, the correlation between the latter waste characteristic and the ammonia content is striking.

Except for the high correlation between suspended solids and the non-soluble COD fraction, i.e., COD-COD (.45), no distinct relations can be deduced among the different wet chemistry data. Clearly, all wastewater characteristics provide different information concerning the wastewater. It is the opinion of the authors that the BOD_{st} is the most appropriate variable for feedforward control of wastewater treatment plants since it quantifies the amount of oxygen that will be consumed within the wastewater retention time in the treatment plant.

Practical Implementation

Three examples are given of the implementation of these respirometric principles in a treatment works.

The first illustration of Figure 7 is one week BOD_{st} data set recorded at the Maria Middelares hospital wastewater treatment plant. One observes the daily variations in influent waste concentration. This is typical for hospital wastewaters: high loads at daytime when staff is present and very low waste content at night. From the data one can also deduce the reduced pollutant concentration during weekends. It is important to note that the principles presented allow one to cover this BOD_{st} range.

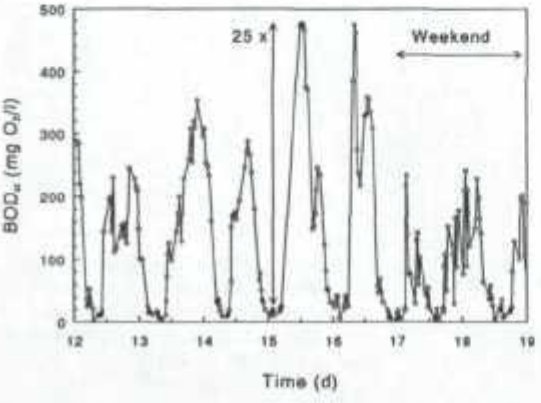

Figure 7. One week influent BOD_{st} data obtained with the one-vessel type respirometer at the Maria Middelares hospital wastewater treatment plant.[20]

As an example of the implementation of such respirometers at an industrial site, the treatment works of Degussa Antwerp is taken. Figure 8 summarizes the wastewater treatment facility for the different production plants operating at this factory of specialty chemicals. The wastewater is collected through two different channels, one of which transports a wastewater with approximately constant concentration to the treatment facility. On this supply route a buffer tank is installed to equalize load variations to the treatment process.

A first one-vessel type respirometer was installed in mid-1991 at the effluent of the primary settler (item 16 in Figure 8). Large variations in the BOD_{st} occur (1200 ± 630 mg O_2/L, n = 1808 over a seven week period) which can be correlated with changes in the batch productions occurring in the firm.

With this respirometer many lab-type tests were performed for treatability and toxicity evaluation of new wastewaters at Degussa Antwerp. This resulted in periodic interruptions of the on-line monitoring of the input wastewater. To sustain the on-line monitoring of the influent BOD_{st}, a second respirometer was implemented in the beginning of 1993 (item 17 in Figure 8). It was situated upstream of the equalization basin because this could lead to an improvement of the load variation control system and would assist in early toxicity detection. At present, studies are going on to use the information provided by both sensors for feedforward control of the pumping from the DOC buffer tank (item 1 in Figure 8) to minimize load variations and economize on energy costs.

Figure 9 shows the application of the two-vessel principle as a verification for an alternative BOD_{st} measurement technique.[19] In this technique the BOD_{st} is estimated from the transients between two modes of respiration measurement at a pilot plant treating municipal wastewater from Bennekom.

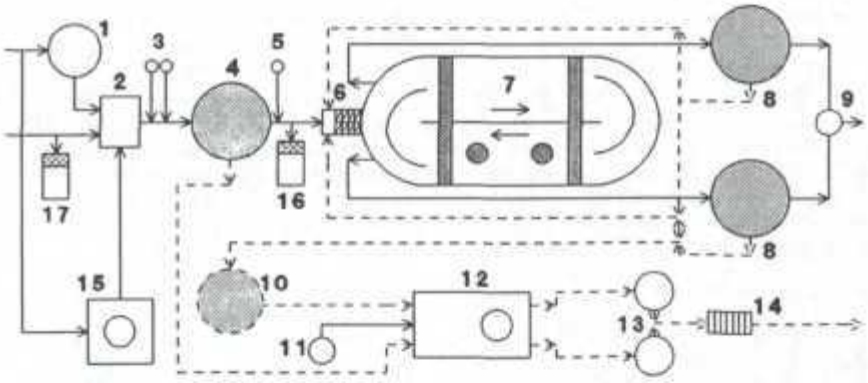

Figure 8. Flow scheme of the waterwater treatment plant of Degussa Antwerp. (1) COD buffer tank; (2) equalization basin; (3) pH control equipment; (4) primary clarifier; (5) p-dosing unit; (6) pumping station; (7) aeration basin; (8) secondary clarifier; (9) effluent tank; (10) sludge thickener; (11) $FeCl_3$/$CaCO_3$ dosing unit; (12) sludge conditioning; (13) sludge buffer tank; (14) sludge filter press; (15) calamity basin; (16) respirometer 1; (17) respirometer 2

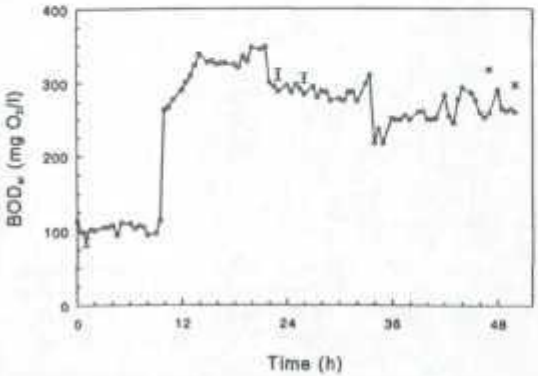

Figure 9. BOD_{st} measurements of Bennekom influent according to the principle described in this paper [points] as a verification of an alternative BOD_{st} measurement [line].

The principle described in this paper was used to verify the estimated BOD_u at arbitrary time instants. The figure shows a good agreement between the two measurement techniques.

CONCLUSIONS

Both respirometric principles can be used to determine the BOD_u of different types of wastewater. The respirometers based on these principles can determine the BOD_u with a relative measuring error of 5%. However, a significant difference of 10% exists between the BOD_u values of both principles. A suitable explanation can not be provided yet and it is suggested one partly repeat the comparison with special emphasis on the behavior of the DO meters, the KLa estimation and the randomization of the experimental setup. In addition, application of the one-vessel principle on the two-vessel data may be a means of explaining the difference. Both meters are suitable for implementation at full-scale industrial activated sludge plants, as illustrated with three cases.

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REFERENCES

1. Buhr, H.O., J.F. Andrews, and T.M. Keinath, "Research needs for automation of wastewater treatment systems," *Proceedings of a U.S. Environmental Protection Agency Workshop*. Clemson University, South Carolina, September 23–25 1974, pp. 135.
2. Andrews, J.F., Review paper: "Dynamic models and control strategies for wastewater treatment processes," *Wat. Res.*, 8, 261–289, (1974).
3. Olsson, G., "State of the art in sewage treatment plant control," *AIChE Symp. Series*, 159, 72, 52–76, (1976).
4. Lech, R.F., C.P.L. Grady Jr., H.C. Lim, and L.B. Koppel, "Automatic control of the activated sludge process. II. Efficacy of control strategies," *Wat. Res.*, 12, 91–99, (1978).
5. von Jeszenszky, T., and I.J. Dunn, "Dynamic modelling and control simulation of a biological wastewater treatment process," *Wat. Res.*, 10, 461–467, (1976).
6. Brett, R.W.J., R.I. Kermode, and B.G. Burrus, "Feed forward control of an activated sludge process," *Wat. Res.*, 7, 525–535, (1973).
7. Vanrolleghem, P.A., and W. Verstraete, "On-line monitoring equipment for wastewater treatment processes: State of the Art," *Proceedings TI-KVIV Studiedag Optimalisatie van Waterzuiveringsinstallaties door Proceskontrole en-sturing*. Gent, Belgium, October 21, 1993, pp. 1–22.
8. *Standard Methods for the Examination of Water and Wastewater*, 17th Edition. American Public Health Association, Washington, DC, 1989.
9. Chudoba, P., B. Capdeville, and J. Chudoba, "Explanation of biological meaning of the So/Xo ration in batch cultivation," *Wat. Sci. Tech.*, 26, 743–751, 1992.
10. Vernimmen, A.P., E.R. Henken, and J.C. Lamb III, "A short-term biochemical oxygen demand test," *J. Water Pollut. Control Fed.*, 39, 1006–1020, 1967.
11. Cech, J.S., J. Chudoba, and P. Grau, "Determination of kinetic constants of activated sludge microorganism," *Wat. Sci. Tech.*, 17(2-3), 121–132, 1985.
12. Arthur, R.M., L.W. Kdent, and R.J. Raymond, "Automatic respirometry—a unique tool for determining design parameters for a cannery domestic wastewater treatment plant," *Proceedings 45th Purdue Industrial Waste Conf.*, Lewis Publishers, Chelsea, MI, 1991, pp. 477–485.
13. Pilz, U., "Unsteril selektive Kulturtechniken and respirometrische Messtechnik fur on-line Biotestgerate," *Workshop Respirometry*, Julich, Germany, November 6–7, 1991.
14. Vandebroek, R., "Study and development of a microcomputer controlled sensor for the determination of the biodegradability and the toxicity of wastewaters: The RODTOX," PhD. Thesis, Fac. Agricultural Sciences. State University of Gent, Belgium. 1986, pp. 171.
15. Vanrolleghem, P.A., "On-line modelling and control of activated sludge processes: Development of an adaptive sensor," PhD. Thesis, Fac. Agricultural and Applied Biological Sciences, University Gent, Belgium, 1994, pp. 201.
16. Spanjers H., "Respirometry in activated sludge," PhD. Thesis, Wageningen Agricultural University, The Netherlands, 1993, pp. 199.
17. Kong, Z., P.A. Vanrolleghem, and W. Verstraete, "An activated sludge-based biosensor for rapid IC50 estimation and on-line toxicity monitoring," *Biosens. Bioelectron.*, 8, 49–58, 1993.
18. Vanrolleghem, P.A., Z. Kong, G. Rombouts, and W. Verstraete, "An on-line respirograhic biosensor for the characterization of load and toxicity of wastewaters," *J. Chem. Technol. Biotechnol.*, (in press), 1994.

19. Spanjers, H., G. Olsson, and A. Klapwijk, "Determining influent short-term biochemical oxygen demand by combining respirometry and estimation," *Wat. Sci. Tech.*, (in press), 1994.
20. Kong, Z., M. Vaerewyk, and W. Verstraete, "The on-site application of the on-line respirometer for monitoring the load and toxicity of wastewater," *Proc. Forum Appl. Biotech.*, Brugge, Belgium, September 28–30, 1994, (Accepted).