

MODELLING OF THE DISSOLVED OXYGEN PROBE RESPONSE IN THE IMPROVEMENT OF THE PERFORMANCE OF A CONTINUOUS RESPIRATION METER

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Abstract—In the present technique for the measurement of the respiration rate, the DO-probe is repeatedly subjected to a step change of the oxygen concentration with a time interval of typically 20–30 s. The end value of each response is used to calculate the respiration rate of activated sludge. However, those end values can be inaccurate because of probe dynamics or probe response time. This paper describes an improved method to measure the dissolved oxygen (DO) concentration with one and the same probe at the inlet and outlet of a respiration chamber. The real DO concentration at the end of each response can be estimated by fitting the DO measurements to a first-order response model of the probe. Furthermore, at each step response the time constant of the probe response can be estimated which provides a continuous diagnosis of the probe condition. The proposed method provides a reliable estimate of the real DO concentration and, as a result, the reliability of the calculated respiration rate is improved. The first-order probe response constant is a useful indicator for fouling of the probe membrane.

Key words—activated sludge process, dissolved oxygen, dissolved oxygen probe, fouling, modelling, respiration rate

NOMENCLATURE

- C = real dissolved oxygen (DO) concentration (mass volume⁻¹)
 h = sampling interval DO concentration (time)
 K = number of measuring points in one response
 t = time (time)
 t_c = first-order probe response time constant (time)
 t_d = dead time (time)
 t_r = response measuring period (time)
 y = DO probe signal (mass volume⁻¹)
 α_0 = offset of real DO concentration at start of response (mass volume⁻¹)
 α_1 = slope of real DO concentration change during one response (mass volume⁻¹ time⁻¹)
 τ = integration variable (time)

INTRODUCTION

The respiration rate of activated sludge is an important variable for the control of the activated sludge process. It provides information as to the loading to the plant (Olsson and Andrews, 1978), the influent and effluent BOD (Spanjers and Klapwijk, 1990), the microbial activity (Vargas Lopez, 1988) and it can indicate toxic effects on the activated sludge (Temmink *et al.*, 1990). In batch experiments respiration rate measurements can be used for studies on biodegradation (Grady *et al.*, 1989), kinetics (Ossenbruggen *et al.*, 1991) and toxicity (Spanjers and Klapwijk, 1986).

Different respiration meters, measuring the uptake of oxygen by the activated sludge, are described in the literature. The manometric respiration meter is based on the measurement of the volume of oxygen gas used by the bacteria (Hisset *et al.*, 1982). Other meters use some oxygen sensing device which measures the oxygen concentration from which the respiration rate can be calculated.

The electrochemical oxygen sensor is based upon the electrochemical reduction of oxygen in an amperometric cell. The electrodes are immersed in an electrolytic solution which is separated from the bulk solution by a semi-permeable membrane. The electrode signal is determined by the diffusion of dissolved oxygen (DO) from the bulk through the membrane. The electrochemical sensor is used in the respiration meter described in this paper. The probe-meter combination will be referred to as the "DO-probe".

Two types of respiration meters where the DO-probe is used can be distinguished: the batch respiration meter and the continuous flow-through respiration meter. A batch meter is operated by withdrawing a sample of activated sludge from the plant into a small vessel, aerating it and then monitoring the decline in the DO concentration with time. The respiration rate is calculated from the slope of the DO decline (Fujimoto *et al.*, 1981; Kaneko *et al.*, 1985). The continuous flow-through meter measures

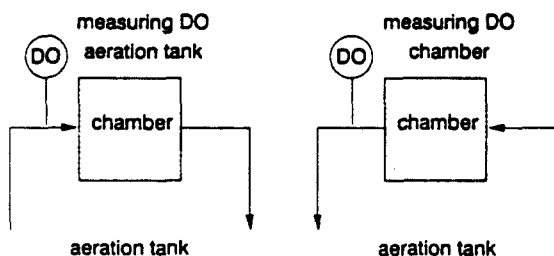


Fig. 1. Scheme of the one-probe continuous respiration meter.

the DO concentration at the inlet and outlet of a closed respiration chamber through which the sludge is pumped continuously (Sollfrank and Gujer, 1985; Spanjers and Klapwijk, 1990). The respiration rate is calculated from the difference of the two DO measurements.

The respiration meter as described by Spanjers and Klapwijk (1987, 1990) has proven its usefulness and its reliability. The characteristic of this meter is that the DO concentration in the inlet and outlet is measured with one single probe, fixed at one opening of the chamber, by alternating the flow direction through the chamber (Fig. 1).

When the DO probe is replaced by another sensor, such as a nitrate or chlorine probe, the measuring technique may also be applied to measure the production or utilization of those compounds. This application will not be considered in this paper.

One problem with this principle is that a steady state DO reading is only available when the DO probe signal, after changing the flow direction, has reached its end value. Hence, the maximum measuring frequency for the DO concentration is limited by the response time of the DO probe. Till now, in practise, the measurement of the DO takes place when the signal has reached about 95% of its ultimate value. The time needed to attain this 95% response (response measuring period) is based on experience. As both the inlet and outlet concentration may be off the real value, a systematic error of about 10% may occur in the calculated respiration rate. Furthermore, a dirty membrane and a consequently slower DO response may result in an even higher error contribution.

A second problem is that at the end of each response measuring period only one concentration is available: either the DO at the inlet or the DO at the outlet. This means that in the calculation of the respiration rate the other DO value had to be estimated. Till now this has been done by means of linear interpolation. This problem will be discussed elsewhere (Spanjers, 1992). For an accurate measurement of the respiration rate it is important to measure both DO concentrations as frequently as possible and to extract maximum information from the probe response.

A general problem with DO probes is that a probe failure caused by, for example, fouling of the mem-

brane, may be interpreted as a change in the DO concentration. When the probe is applied in a respiration meter, the failure is interpreted as a change in the respiration rate (Temmink, 1992).

In this paper a first-order probe response model is proposed. Due to a short measurement time the steady state DO concentration has not been reached. Then the final DO concentration can be estimated from the model. Furthermore the first-order probe response time constant will be estimated after each response, which can be used for probe performance diagnosis. The estimation method is based on a least squares fit. Simulations and batch experiments are used to demonstrate the effectiveness of the method.

MODEL OF THE DO-PROBE RESPONSE

It is assumed, and experimentally verified, that the DO probe signal can be modelled by a first-order dynamic system and that the change of the real DO concentration during the response measuring period (typically 20–30 s) will change along a linear slope. The response of the DO probe after a change in the flow direction can then be considered as a combined step and ramp response of a first-order system (Fig. 2).

The DO probe signal y is modelled by a first-order dynamic system:

$$t_c \frac{dy}{dt} = -y + C \quad (1)$$

where the input C is the real DO concentration which is assumed to be a ramp function with offset α_0 and slope α_1 :

$$C = \alpha_0 + \alpha_1 t. \quad (2)$$

Combining (1) and (2) gives the response function:

$$t_c \frac{dy}{dt} = -y + \alpha_0 + \alpha_1 t. \quad (3)$$

There is an analytical solution of (3) that can be written in the form:

$$y(t) = e^{-t/t_c} y(0) + \int_0^t e^{-(t-\tau)/t_c} u(\tau) d\tau \quad (4)$$

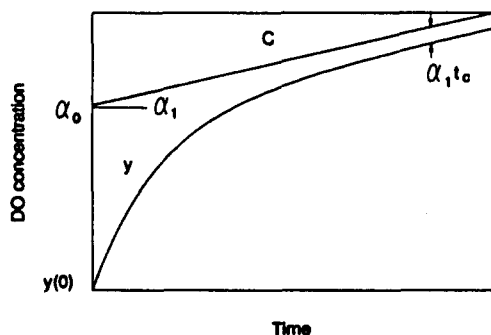


Fig. 2. Combined step and ramp response of the DO probe after changing the direction of the sludge flow. First-order linear system assumed.

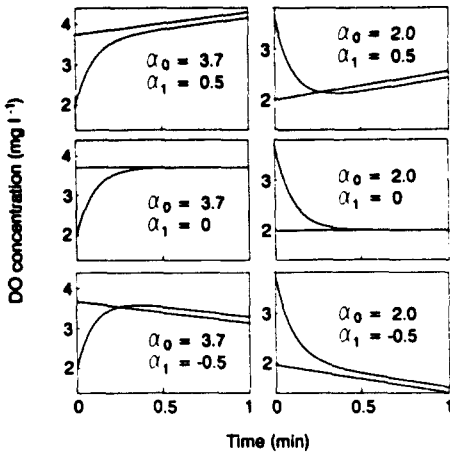


Fig. 3. Simulation, using equation (5), of the measured DO (y) after reversing the sludge flow direction, i.e. after a step change in the DO (C) followed by a time linear change of C . Probe response time constant $t_c = 0.10$ min.

where

$y(0)$ = the initial condition of the probe signal at time $t = 0$.

$$u = (\alpha_0 + \alpha_1 t) / t_c.$$

Inserting the value of u gives the DO response as a function of time:

$$y(t) = [(y(0) - \alpha_0 + \alpha_1 t_c) e^{-t/t_c}] + [\alpha_0 + \alpha_1 t] - [\alpha_1 t_c]. \quad (5)$$

It is recognized that the first term of (5) converges to 0 after some time, determined by the probe response time. The last term of (5) is then seen to show the lag between the real DO concentration and the probe response after the transient. Figure 3 shows the result of a simulation using (5) for different realistic values of the parameters. The simulation demonstrates that, when the real DO concentration changes along a linear slope, the ultimate value of the DO signal (y) always deviates $\alpha_1 t_c$ from the real DO concentration (C).

ESTIMATION OF DO CONCENTRATION AND PROBE RESPONSE TIME CONSTANT

All three parameters t_c , α_0 and α_1 in equation (3) are unknown and have to be estimated from the DO probe step response. Since the DO measurements are obtained in time discrete form it is straightforward to approximate the time derivative in (3) with finite differences. Here we choose the trapezoidal rule for integration:

$$t_c \frac{y_{k+1} - y_k}{h} = \frac{1}{2}(-y_{k+1} - y_k + \alpha_0 + \alpha_1 k h + \alpha_0 + \alpha_1 (k+1)h) \quad (6)$$

where

$$k = 1, 2, \dots, K; K \text{ typically } 10 \text{ or } 15$$

$$h = \text{sampling interval DO concentration, typically } 1 \text{ or } 2 \text{ s.}$$

The parameter α_1 can be estimated separately. Here we consider the last DO measurement of two consecutive step responses, called $y_K(m-1)$ and $y_K(m)$. The DO concentration slope is then estimated from:

$$\alpha_1 \approx \frac{y_K(m) - y_K(m-1)}{2Kh}. \quad (7)$$

Now there remain two parameters, t_c and α_0 , to be estimated. If equation (6) is applied to all K measurements (but the first) in one step response we obtain:

$$\begin{aligned} t_c(y_2 - y_1) - h\alpha_0 &= \frac{1}{2}h(-y_2 - y_1 + 3h\alpha_1) \\ t_c(y_3 - y_2) - h\alpha_0 &= \frac{1}{2}h(-y_3 - y_2 + 5h\alpha_1) \\ &\vdots \\ t_c(y_K - y_{K-1}) - h\alpha_0 &= \frac{1}{2}h(-y_K - y_{K-1} + (2K-1)h\alpha_1). \end{aligned} \quad (8)$$

This can be written in a vector form:

$$\begin{bmatrix} y_2 - y_1 & -h \\ y_3 - y_2 & -h \\ \vdots & \vdots \\ y_K - y_{K-1} & -h \end{bmatrix} \begin{bmatrix} t_c \\ \alpha_0 \end{bmatrix} = \begin{bmatrix} \frac{1}{2}h(-y_2 - y_1 + 3h\alpha_1) \\ \frac{1}{2}h(-y_3 - y_2 + 5h\alpha_1) \\ \vdots \\ \frac{1}{2}h(-y_K - y_{K-1} + (2K-1)h\alpha_1) \end{bmatrix} \quad (9)$$

or written in a more compact form:

$$\phi\theta = y. \quad (10)$$

The unknown parameter vector θ can be estimated by the least-squares method (Åström and Wittenmark, 1984):

$$\hat{\theta} = (\phi^T \phi)^{-1} \phi^T y. \quad (11)$$

The estimate $\hat{\theta}$ makes it possible to calculate the DO concentration at the end of the sampling interval:

$$C(m) = \hat{\alpha}_0 + \hat{\alpha}_1 Kh. \quad (12)$$

This is used for a new estimation of α_1 :

$$\alpha_1 \approx \frac{C(m) - C(m-1)}{2Kh} \quad (13)$$

$C(m-1)$ is the calculated real DO from the foregoing response. Then a new vector θ is calculated from the observations y . This procedure is repeated until a present error criterion is met.

This method was tested by means of two simulations and an experiment. The application of the method was demonstrated in another experiment where the probe membrane was fouled intentionally.

MATERIALS AND METHODS

In the simulations, executed with SIMNON (Elmqvist *et al.*, 1986), the measuring data were generated using the first-order model (5) and chosen values of C and t_c . Then the method proposed was used to recalculate C and t_c . Any deviation of the result from the original C and t_c emanates from the assumption that the time derivative of (3) can be approximated by the trapezoidal integration method.

In the laboratory experiments a respiration meter RA1000, Manotherm, equipped with a WTW dissolved oxygen meter (modified model OXY-219/R with sensor model E090), was connected to an aerator, the total system having a content of 1.5 l. of activated sludge. The sludge was sampled from a nitrifying activated sludge plant. The respiration meter, which works according to the principle described by Spanjers and Klapwijk (1990), was operated in a mode such that the alternating DO signal could be sampled. Temperature and pH were kept constant at 20°C and 7.5, respectively.

In one experiment the assumption of the first-order model was tested. Therefore, a known amount of ammonium was added to the sludge and the DO signal was recorded. The DO concentration at the inlet and at the outlet were either calculated from 2 to 4 values at the end of the response measuring period (averaging method) or calculated according to the method proposed in this paper (estimation method). From the DO concentrations, the respiration rate and the mass of oxygen used by the nitrifiers for the oxidation of one unit of mass nitrogen (O/N ratio) (Spanjers and Klapwijk, 1990) were calculated, respectively. The O/N ratio was compared for different situations.

In the other experiment the procedure to detect probe failure from an increasing t_c was tested. Probe fouling was imitated by covering a part of the probe membrane with ball-bearing grease. Ammonium was added to the sludge before and after contamination of the membrane. The effect on t_c and on the O/N ratio was studied.

VERIFICATION OF THE METHOD

Linear change of the real DO concentration (simulation 1)

For given constant values of α_1 , h and t_c , and an initial value of α_0 , equation (5) was used to simulate the course of the measured DO during a short period of respiration measurement (Fig. 4). In this simulation it was assumed that the respiration rate was decreasing linearly. Normally distributed noise was added to the calculated value of the DO.

The simulated DO values were used to estimate t_c and C employing equations (7)–(13). Figure 5 shows the result.

In case of an optimal estimation procedure, the resulting t_c and C would have been the original

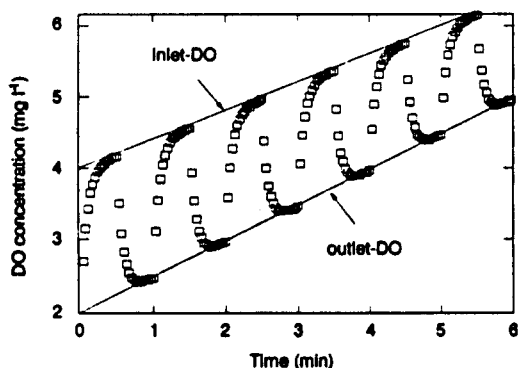


Fig. 4. Simulation, using equation (5), of the measured DO concentration (points) during the operation of the respiration meter in comparison to inlet and outlet DO (solid lines). $h = 2$ s, $t_c = 0.08$ min, $t_r = 0.5$ min, $\alpha_0 = 4$ and 2 g m⁻³, $\alpha_1 = 0.4$ and 0.5 g m⁻³ min⁻¹ for, respectively, the inlet and outlet. Standard deviation noise: 0.008 g m⁻³.

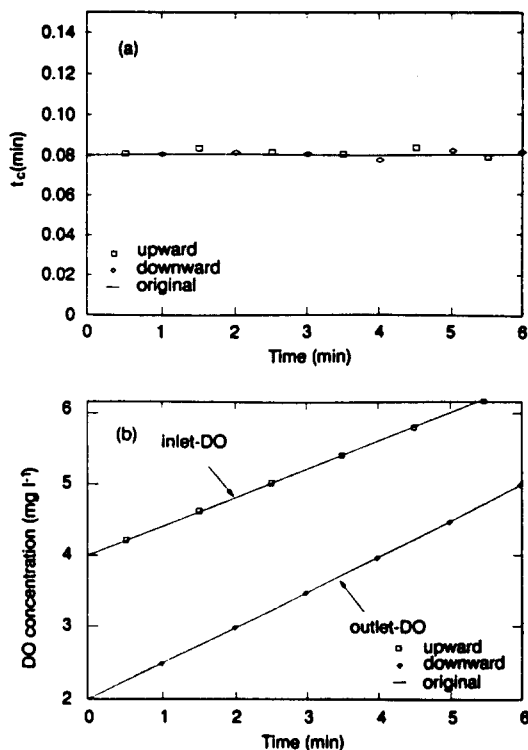


Fig. 5. Result of the estimation method applied on the simulated DO probe values (Fig. 4). Calculated values (points) compared with originally simulated values (solid lines). (a) Probe response time constant (t_c) and (b) real DO concentration (C).

values. The figure shows that t_c (mean value 0.079 ± 0.002 min) and C are estimated well.

Non-linear change of the real DO concentration (simulation 2)

A batch experiment with the continuous flow-through respiration meter was simulated to test the assumption that, within the response measuring period, the change of the real DO concentration can

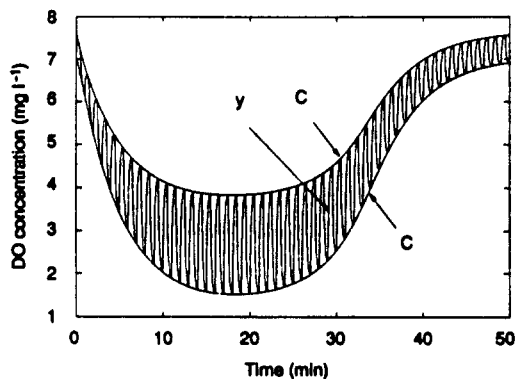


Fig. 6. Simulation of a batch experiment. Addition of 0.010 g ammonium-nitrogen to 1.5 l. sludge. Michaelis-Menten constants: half-saturation constant = 1.5 g ammonium-nitrogen per m³; maximum respiration rate = 65 g m⁻³ h⁻¹; probe time constant (t_c): 0.1 min; standard deviation noise: 0.01 g O₂ m⁻³; response measuring period (t_r): 30 s.

be accurately represented by a linear relationship. In this experiment an amount of ammonium was added to the aerator connected to the respiration meter. The simulation model included Michaelis-Menten kinetics and a set of dynamic mass balances on DO and substrate for the aerator and the respiration chamber. The parameters were chosen from a fit of the simulation model on the experimental results of Spanjers and Klapwijk (1990). In this simulation, unlike simulation 1, the change of the simulated DO is not linear any longer. Even so, in the calculation of t_c and C , it is assumed to be linear within the response measuring interval.

Figure 6 shows the simulated DO concentration at the inlet and at the outlet of the respiration chamber as well as the simulated response of the DO probe.

The simulated DO probe measurement values were used to estimate t_c and C with the equations (9)–(13). Figure 7 shows the result.

As in simulation 1, t_c and C are estimated well (Fig. 7). t_c does not depend on the magnitude of the response. The estimated DO is very close to the originally simulated DO.

From the results of the simulations it is concluded that the method proposed here allows the estimation of the first-order probe response time constant and the real DO concentration.

Experimental verification of the first-order model

To test the assumption of the first-order model, the experiment described and simulated in simulation 2 was carried out in the laboratory. In three experimental runs, the response measuring period (twice 15 s

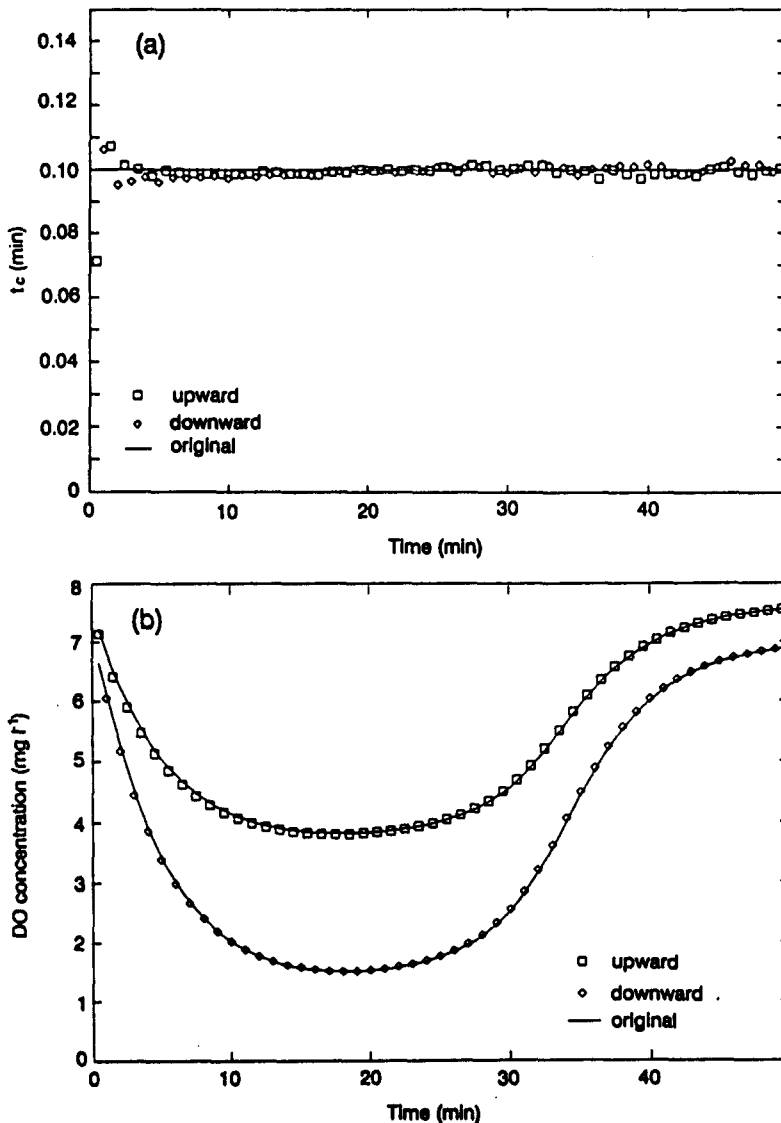


Fig. 7. Result of the estimation method for C and t_c applied on the simulated DO probe values (Fig. 6). Estimated values (points) compared with the originally simulated values (solid lines). (a) Probe response time constant (t_c) and (b) real DO concentration (C).

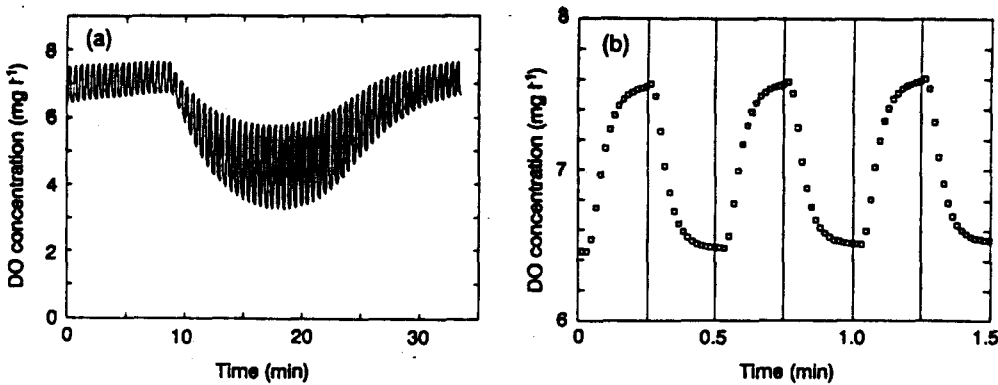


Fig. 8. DO probe signal in a batch experiment: addition of 5 mg N as ammonium to activated sludge. (a) Full experiment and (b) first 1.5 min of the experiment.

and once 20 s) was too short to attain the steady state response. Therefore this experiment was well suited to demonstrate the capability of the method to estimate the real DO concentration in the inlet and outlet of the respiration chamber. Figure 8 shows the DO-probe signal.

Figure 9(a) shows the estimated t_c for both the upward and the downward response. t_c from the upward response is higher than t_c from the downward response. Apparently, the model applied is not completely valid for both the upward and downward responses or both. After careful examination of the shape of the response curves [Fig. 8(b)] in relation to the geometry of the respiration meter (there was a dead space in one flow direction) it was concluded that a dead time (t_d) had to be incorporated in the model (3):

$$t_c \frac{dy}{dt} = -y + \alpha_0 + \alpha_1(t - t_d) \tag{14}$$

t_d depends on the flow direction. In the experiments reported here, the values were found by trial and error to be 2 and 1 s for the measurement of the inlet DO concentration and the outlet DO concentration, respectively. Figure 9(b) shows that when the dead time is accounted for, both responses

produce almost similar t_c which also show less variation. As in simulation 2, t_c is independent of the response amplitude.

The DO concentrations at the inlet and at the outlet of the respiration chamber were calculated by averaging three measurements at the end of each response (averaging method) and by the method proposed in this paper (estimation method). Next, the respiration rate was calculated as described by Spanjers and Klapwijk (1990). The result is shown in Fig. 10.

The estimation method results in higher values for the respiration rate, especially at a higher rate when the difference between inlet and outlet DO concentration is greater. It is difficult to verify the correctness of the absolute value of the respiration rate. Therefore, from the respiration rate, the total amount of oxygen additionally used for the endogenous oxygen consumption, defined as short-term biochemical oxygen demand (BOD_{ST}), was evaluated for both results. The BOD_{ST} was calculated from the area under the respiration curves. This value divided by the amount of nitrogen added represents the mass of oxygen used by the nitrifiers for the oxidation of one unit of mass nitrogen (O/N ratio). Table 1 summarizes the results for the same experiment repeated with different response measuring periods.

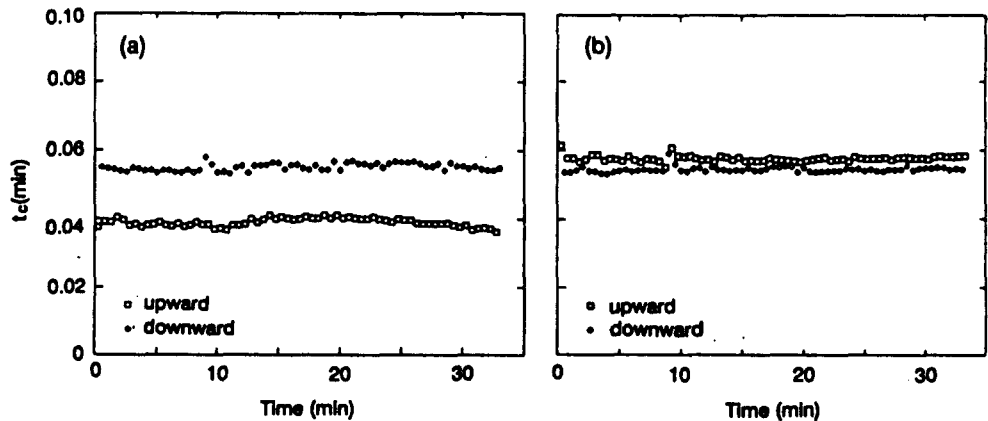


Fig. 9. t_c calculated from the DO probe measurement. (a) Without correction for dead time and (b) with correction for dead time.

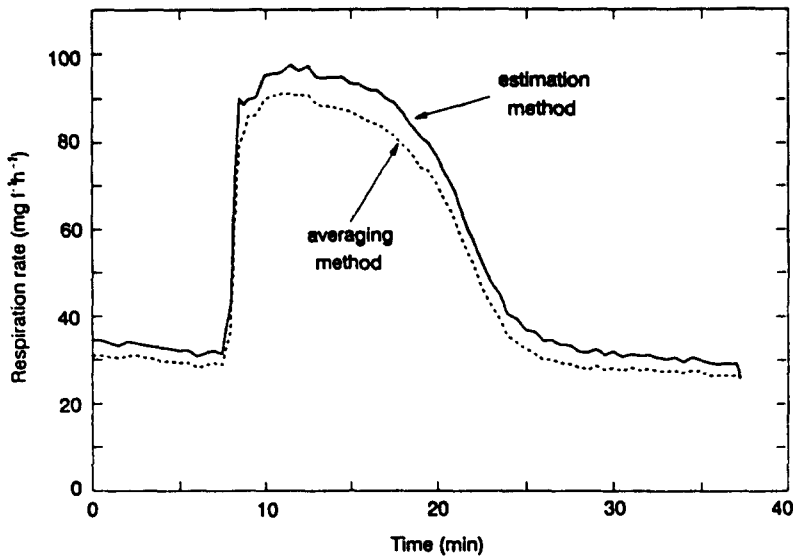


Fig. 10. Respiration rate calculated from the DO probe signal in Fig. 8. Comparison of the averaging method and the method proposed in this paper.

From Table 1 two conclusions can be drawn. Firstly, for a short response measuring period, the averaging method yields lower values for the O/N ratio while the estimation method produces equal values as compared to a large response measuring period. This means that the estimation method produces a better estimate of the real DO concentration. Two experiments yield a low O/N value from the estimation method compared to the value in the literature.

Secondly, the negligible difference between the two methods at a response measuring period of 30 s indicates that the effect of a changing real DO concentration on the probe response is marginal, for in the determination of the O/N ratio there is a sharp change of the DO at only two different occasions. Another reason for the small difference is that the shift in the endogenous as well as in the maximum respiration rate reduces the impact on the total amount of oxygen calculated from the area under the curve. Nevertheless, in kinetic experiments, when transients in the respiration rate and thus in DO concentration become important (Ossenbruggen *et al.*, 1991), the effect of changing the real DO will become stronger in the probe response.

Table 1. Comparison of the averaging method (average of three measurements at the end of the response measuring period) and the estimation method proposed in this paper for different response measuring periods (t_r). Theoretical value O/N: 4.75; expected value: 4.4 (Spanjers and Klapwijk, 1990)

| O/N | | | | |
|------------|--------------|---------------------|----------------------|------------------------------|
| h (s) | t_r (s) | Averaging method | Estimation method | Reference |
| 1 | 15 | 3.91 | 4.26 | This investigation |
| 1 | 15 | 3.74 | 4.01 | This investigation |
| 2 | 20 | 4.29 | 4.39 | This investigation |
| 2 | 30 | 4.02 | 4.04 | This investigation |
| 2 | 30 | 4.33 | 4.38 | This investigation |
| — | 30 | 4.36 | — | Spanjers and Klapwijk (1990) |
| — | — | — | 4.33 | Sharma and Ahlert (1977) |

From the experiments it is concluded that, for incomplete responses, the estimation method produces a better estimate of the real DO concentration and consequently a better result for the calculated respiration rate. Because of the actual geometry of the respiration meter, a correction in the response model for dead time is required.

DETECTION OF PROBE FOULING USING THE PROBE RESPONSE TIME CONSTANT

In batch experiments it was attempted to detect probe failure from the estimated t_c . Therefore, the probe membrane was contaminated intentionally by covering part of the membrane with a thin layer of grease (approx. 10–25% of the surface).

First it was established that the contact of approximately the same amount of grease with the sludge in the aerator had no impact on either the DO concentration or the respiration rate. This means that the substance is not biodegradable or toxic on a short term and that it should neither provoke a change in the respiration rate when it is applied to the membrane surface.

Two experiments were carried out. In the first experiment an amount of grease was applied twice to the membrane, while the respiration meter was measuring the endogenous respiration rate. In Fig. 11(a) the estimated t_c is shown and the applications of grease are indicated. The figure shows that a greater amount of grease results in an increasing t_c , meaning that the probe becomes slower. Consequently, the DO concentration calculated from the end values of the response measuring period (averaging method) is erroneous and so is the calculated respiration rate [Fig. 11(b)]. The DO from the estimation method, and therefore the calculated respiration rate are affected to a lesser extent by the deterioration of the probe: after the first treatment

the rate decreases from 20 to 15 mg l⁻¹ h⁻¹; after the second treatment it remains at this level, although the noise has increased. This decrease may partly be caused by another incident, for example the real endogenous respiration rate may have decreased

during the time that the membrane was being contaminated. This is supported by the check at the end of the experiment where the membrane was replaced by a new one and the respiration rate was found to be 18 mg l⁻¹ h⁻¹.

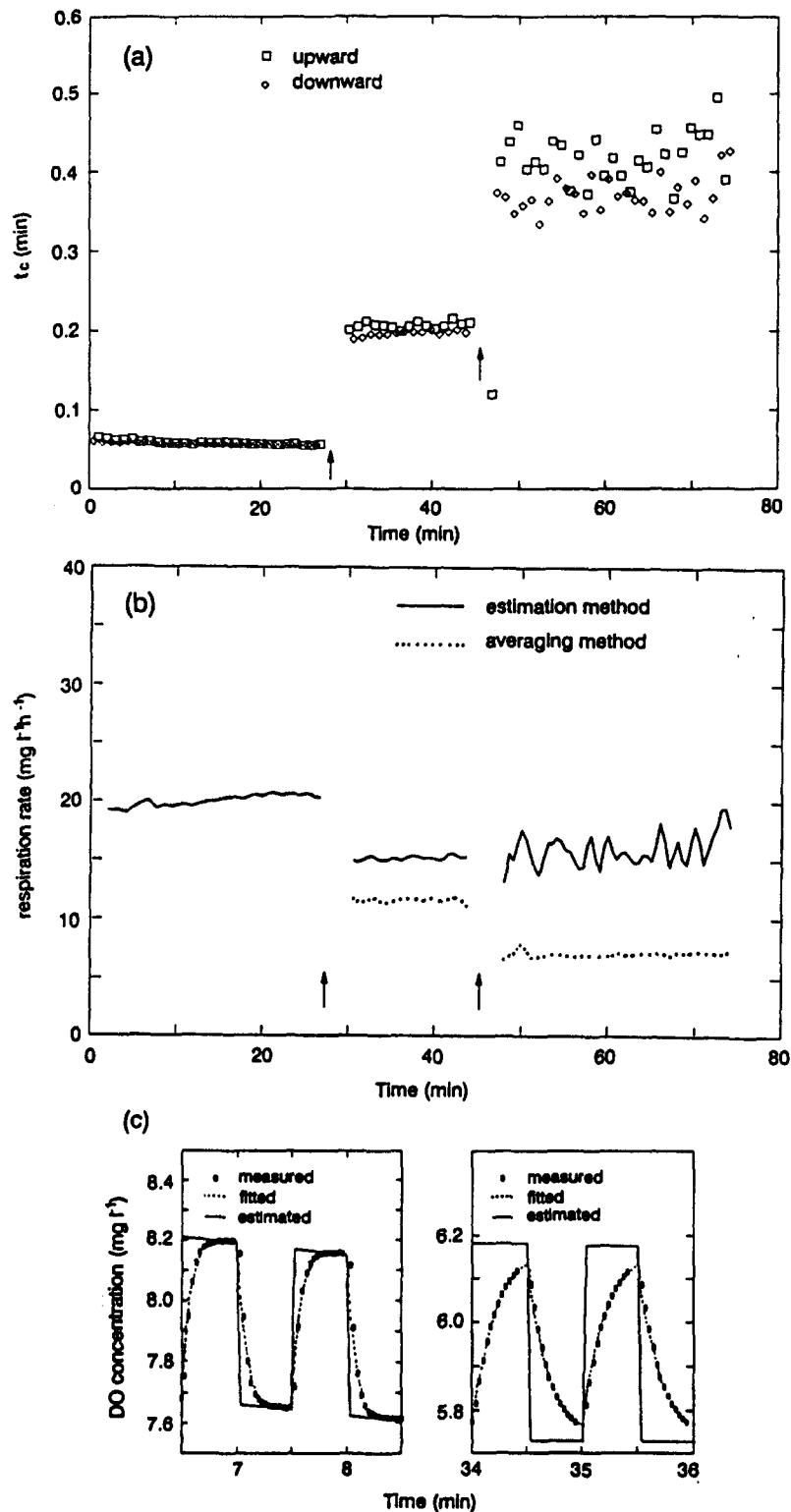


Fig. 11. Effect of the concentration of the probe membrane. (a) Probe response time constant, (b) respiration rate; comparison averaging method and estimation method and (c) part of the probe signal (points) before and after contamination (respectively left and right), in comparison with the estimated DO.

Figure 11(c) illustrates the effect of the contamination on the individual response curves. In this figure the estimated DO is also indicated.

In the second experiment ammonium was added twice to activated sludge in the endogenous phase of respiration. The first addition is already reported in the previous section (Fig. 10 and Table 1). The second addition was done after contamination of the membrane. Figure 12(a) shows the respiration rate calculated from the DO concentration, whereas t_c is plotted in Fig. 12(b). The O/N ratio was calculated from the respiration rate (Table 2).

From Table 2 it can be concluded that the O/N ratio evaluated from the estimation method is not affected by the probe deterioration while the O/N ratio from the averaging method (already lower because of the short response measuring period, see Table 1) is decreased.

DISCUSSION

The purpose of this investigation was to improve the measurement of the DO concentration with one

Table 2. Effect of the contamination of the probe membrane on the calculated O/N value. Comparison of the averaging method (averaging three measurements at the end of the response measuring period) and the estimation method proposed in this paper. $h = 1$ s, $t_r = 15$ s, theoretical O/N ratio: 4.57

| | O/N | |
|----------------------|------------------|-------------------|
| | Averaging method | Estimation method |
| Before contamination | 3.91 | 4.26 |
| After contamination | 3.04 | 4.28 |

and the same probe at the inlet and at the outlet of a respiration chamber. Inherent in the principle of the respiration meter is that the DO probe is repeatedly subjected to step changes in the DO concentration. This fact is employed, for the improvement of the DO measurement, by fitting a first-order response model to each measured response, which provides an estimation of the real DO concentration and of the first-order probe response time constant. The change of the real DO concentration during the response measurement is accounted for in the model.

The simulations show that the method allows the calculation of C and t_c . On the condition that the probe signal can be modelled by a first-order dynamic

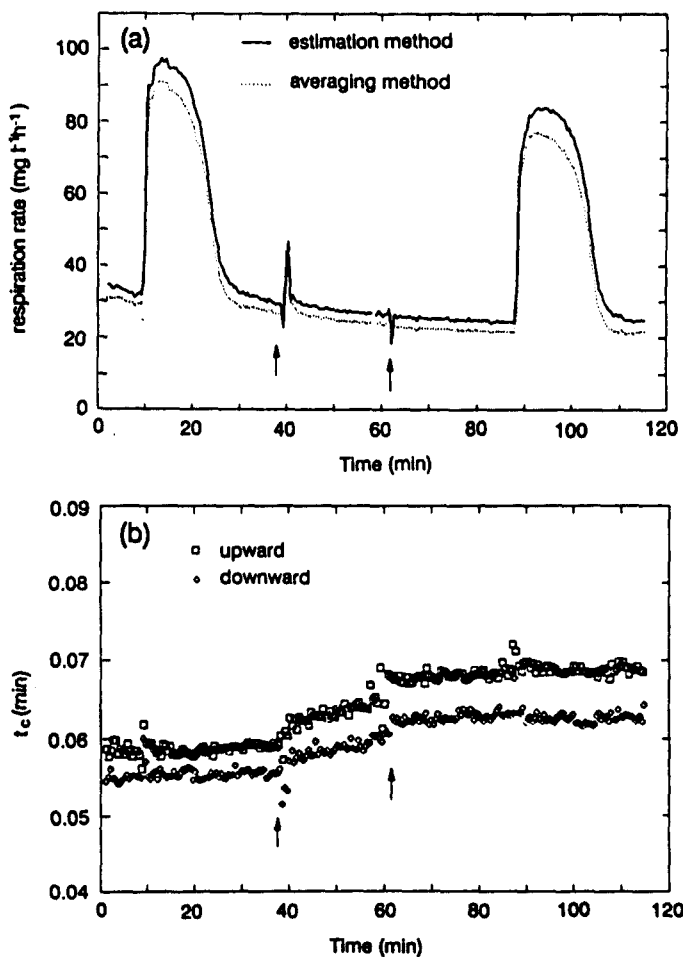


Fig. 12. Addition of 0.005 gN (as ammonium) to 1.5 l. of activated sludge, before and after contamination of the probe membrane. (a) Respiration rate calculated from the DO concentration. Comparison of the averaging method and the method proposed in this paper and (b) probe response time constant (t_c). Arrows indicate contaminations.

system, a correct estimation of C and t_c can be obtained from experimental data. The type of the response is chiefly determined by the manufacturer of the DO meter. However, the response is also partly determined by conditions of the respiration meter in which the probe is mounted. The experiments show that, in this case, the assumption of a first-order response is reasonable, provided a dead time is accounted for. This dead time is fixed by the respiration meter and can be determined exactly by measuring the dead space. The experiments also show that it is reasonable to assume that the change of the real DO concentration within one response measuring period can be approximated by a linear relationship. This can be clearly illustrated by looking at an enlarged portion of Fig. 8(a).

The DO concentration C can be estimated from only a part of the probe response, where the signal has not yet reached its steady state. The advantage of this, in the respiration measurement, is that the measuring frequency of the DOs at the inlet and outlet, and herewith the measuring frequency of the respiration rate, can be increased.

t_c indicates malfunction of the probe even in the case of severe deterioration [Fig. 11(a)], when the probe becomes very slow and the estimation of C probably becomes unreliable.

The method proposed in this paper, for the estimation of t_c and C , can also be used, in combination with the measuring technique, in the measurement of the DO concentration in an activated sludge reactor. On the condition that the respiration meter is installed close to the reactor, the DO concentration in the inflow of the respiration meter is equal to the concentration in the reactor at the sampling point. Besides the measurement of the DO concentration and the optional measurement of the respiration rate this technique, through the estimated t_c , provides a continuous diagnosis of the probe condition.

CONCLUSIONS

The method proposed in this paper provides a reliable estimate of the real DO concentration from the probe response signal when the probe is subjected, in the respiration measurement, to a repeated, stepwise changing DO concentration. As a result, the reliability of the calculated respiration rate is improved.

The first-order probe response constant, evaluated from the probe signal is a useful indicator for fouling of the probe membrane.

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