Respirometry in Control of the Activated Sludge Process: Principles

By

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RESPIROMETRY IN CONTROL OF THE ACTIVATED SLUDGE PROCESS: PRINCIPLES

by

IAWQ TASK GROUP ON RESPIROMETRY

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Preface

The activated sludge process is required to meet effluent standards while keeping investment, sludge production and energy consumption as low as possible. A problem inherent in achieving this aim is that the activated sludge process is highly dynamic because of variations in influent flow rate, concentration and composition. To meet effluent standards at minimum costs, control strategies must be applied that can cope with the dynamic character of the activated sludge process. Essential for the application of control is that the condition of the activated sludge process be observed. For this purpose it is crucial to measure several process variables.

Respiration rate is a variable that has been generating much interest for use in control of the activated sludge process. However, there has been some controversy as to the utility of this variable. This is due partly to inadequate measuring techniques and partly to a lack of understanding of the information content of respirometric data. Furthermore, confusion arising from inconsistency in implementation methods has hindered the introduction of respirometry-based control. As a result, there is still a lack of well-documented respirometry-based control strategies.

Realizing the need for an extensive evaluation of respirometry in control of the activated sludge process, in 1993 the International Association on Water Quality (IAWQ) established a Task Group with the mission to write a Scientific and Technical Report (STR) on the measurement and application of respiration rate in control of the activated sludge process. The aim of this STR was to generate new insights by evaluating existing knowledge present in the literature and practice and to develop a how-to-do protocol. However, the Task Group discovered that the state-of-the-art of respirometry-based control strategies provides insufficient justification for the development of a how-to-do protocol. Therefore, in 1996, the IAWQ agreed to redefine and extend the mission of the group in two stages:

(1) development of a report on the state-of-the-art summarizing principles of measurement and control strategies
(2) development of a report evaluating existing control strategies and providing a how-to-do protocol for existing and new strategies.

This document is the first report. The second report is envisaged for publication in the year 2000.

This report is directed at an audience of researchers and practitioners dealing with the operation and control of activated sludge processes, and it can also be used as a primer on respirometry for students.

The report deals only with measurement of oxygen (not nitrate) respiration. It is not restricted to activated sludge, but also applies to other aerobic biological wastewater treatment processes. Furthermore, only control strategies are considered in which respirometric measurements are used. The Task Group is aware of the fact that control strategies are often not based on respirometry alone. Because of the strong relationship between respiration rate and dissolved (DO) concentration, it is not easy to distinguish between respirometry-based control and DO-based control. In this report, however, pure DO control, i.e. controlling DO by manipulating aeration intensity, is not considered as a form of respirometry-based control.

The report is organized as follows. After a short introduction, the biochemical fundamentals of respiration, its modelling and assessment are reviewed. Then, a major contribution of the Task Group is presented, i.e. a new classification of respirometric measuring principles. The variables measured and deduced with respirometry are subsequently summarized. Next, the basics of control systems are provided, followed by a structured overview of respirometry-based control strategies found in the literature. Finally, some concluding remarks are made.

All the information in the report is correct up to the end of 1997.

Since the discovery of the activated sludge process, a vast amount of literature on respirometry in operation and control of the process has been accumulated. The Task Group has made a thorough study of this literature and has incorporated all the information into this report. Because referring to all the literature would impair the readability of the report, the Task Group decided to omit references from the text and include a structured literature list in an appendix. In addition, the list will be published, and regularly updated, on the World Wide Web page of IAWQ. Any interested reader is invited to browse through the references, search with keywords or download the list.

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Nomenclature

Most important symbols

$(1 - f'_P)$	fraction of biomass utilizing oxygen during endogenous conditions
B_I	inhibitor loading rate
B_V	volumetric loading rate
B_X	sludge loading rate
b_A	decay rate autotrophic biomass
b_{mA}	maximum decay rate autotrophic biomass
b'_H	decay rate heterotrophic biomass (traditional model)
b'_{mH}	maximum decay rate heterotrophic biomass (traditional model)
C_O	O_2 in the gas phase
$C_{O,in}$	O_2 in the gas entering the system
F_{in}	flow rate of the gas entering the system
F_{out}	flow rate of the gas leaving the system
I	percentage inhibition
f_{Qww}	influent flow distribution
K_La	oxygen mass transfer coefficient
K_{NH}	autotrophic saturation coefficient for S_{NH}
K_S	heterotrophic saturation coefficient for S_S
K_{OA}	autotrophic saturation coefficient for oxygen
K_{OH}	heterotrophic saturation coefficient for oxygen
Q_{in}	flow rate of liquid entering the system
Q_{out}	flow rate of liquid leaving the system
Q_{ras}	flow rate of return activated sludge
Q_{store}	flow rate of sludge storage
Q_{was}	flow rate of waste sludge
Q_{ww}	flow rate of influent
$r_{NH,max}$	maximum nitrification rate
r_O	respiration rate
$r_{O,act}$	actual respiration rate
$r_{O,end}$	endogenous respiration rate
R_O	specific respiration rate
S_{NH}	ammonium
S_{NO}	nitrite + nitrate
S_{NO_2}	nitrite
S_S	readily biodegradable substrate
S_O	DO in the liquid phase
$S_{O,in}$	DO in the liquid entering the system
S_O^*	saturation DO in the liquid phase
T_{cycle}	cycle length in periodic process
V_G	volume of the gas phase
V_L	volume of the liquid phase
X	total solids (mixed liquor suspended solids)
X_A	autotrophic biomass
X_H	heterotrophic biomass
X_P	inert matter
X_S	slowly biodegradable matter
Y_A	yield autotrophic biomass
Y_H	yield heterotrophic biomass
μ_A	specific growth rate autotrophic biomass
μ_H	specific growth rate heterotrophic biomass
μ_{mA}	maximum specific growth rate autotrophic biomass
μ_{mH}	maximum specific growth rate heterotrophic biomass
θ_X	sludge age

Abbreviations and acronyms

BOD	biochemical oxygen demand
BODst	short term biochemical oxygen demand
DO	dissolved oxygen
FB	feedback
FF	feedforward
GFS	gas-phase principle with flowing gas phase and static liquid phase
GFF	gas-phase principle with flowing gas phase and flowing liquid phase
GSF	gas-phase principle with static gas phase and flowing liquid phase
GSS	gas-phase principle with static gas phase and static liquid phase
LFS	liquid-phase principle with flowing gas phase and static liquid phase
LFF	liquid-phase principle with flowing gas phase and flowing liquid phase
LSF	liquid-phase principle with static gas phase and flowing liquid phase
LSS	liquid-phase principle with static gas phase and static liquid phase
MIMO	multiple input, multiple output
SBR	sequencing batch reactor
t.t.e.	time to endogenous

Respirometric attributes

at	aeration tank
eff	effluent
exc	excess substrate
inst	instantaneous
intm	intermediate
intv	interval
neg	negligible
ras	return activated sludge
resp	respirogram
rl	return liquor
scul	specific culture
ssub	specific substrate
S_{t0}/X_{t0}	initial substrate-to-biomass ratio
ww	wastewater

1. Introduction

Respirometry is the measurement and interpretation of the biological oxygen consumption rate under well-defined experimental conditions. Because oxygen consumption is directly associated with both biomass growth and substrate removal (see Chapter 2), respirometry is a useful technique for modelling and operating the activated sludge process. In the early years, application of the technique was focused mainly on measurement of the biochemical oxygen demand (BOD) of (waste) water. At that time, respirometry was seen as an instrument-based alternative to the original BOD test, which needed a chemical analysis of dissolved oxygen concentration. Later, starting in the 1960s, respirometry was developed further and the technique began to generate much interest in process control. During the past decade, respirometry has increasingly been employed to obtain biokinetic characteristics, and it is considered one of the most important information sources in activated sludge process modelling (see also the Appendix 'Literature on respirometry').

Since the discovery of the activated sludge process at the beginning of the twentieth century it has been recognized that the rate at which activated sludge consumes oxygen, the **respiration rate**, is an important indicator of the process condition. Consequently, efforts have been made to measure this variable. Respiration rate is usually measured with **respirometers**. These range from very simple manually operated bottles (for example those normally used for BOD measurements) to fully self-operating instruments that automatically perform sampling, calibration and calculation of respiration rate. All respirometers are based on some technique for measuring the rate at which biomass takes up **dissolved oxygen** (DO) from the liquid (see Chapter 3). This can be done directly by measuring DO or indirectly by measuring **gaseous oxygen**. Electrochemical DO measurements (e.g. based on the Clark cell) are almost uniquely applied in DO-based respirometers. Gaseous oxygen concentration can be measured by physical techniques such as the paramagnetic method. Other physical techniques such as manometric and volumetric methods measure the change of gaseous oxygen concentration. In the early years all respirometers were based on gaseous measuring methods. After the introduction of the electrochemical Clark-type DO measuring cell in 1959, this type of sensor became more and more common in respirometers. Currently about 50% of the commercial respirometer brands are based on a DO sensor; see also the Appendix 'Manufacturers of respirometers'. Although it is chiefly commercial respirometers that are used in wastewater treatment practice, a considerable number of home-made respirometers, of which most are of the DO-sensor type, are operational in research environments.

The **basic objective** of wastewater treatment is to keep the plant running while achieving a low concentration of biodegradable matter and nutrients in the effluent at the lowest possible cost. Effluent concentrations and treatment costs are strongly influenced by the rates at which the biomass grows and substrates are removed. Because respiration rate is directly linked to substrate removal and biomass growth, it is obvious that respirometry is an effective tool in the control of the activated sludge process. However, neither respiration rate nor other process variables are generally deployed directly in conjunction with control strategies to secure the basic objective. To achieve the basic objective a number of **operational objectives** have to be specified, such as: maintenance of adequate loading and aeration intensity, accomplishment of denitrification and preservation of good settling properties. Likewise, further specifying the objectives, more specific control objectives have to be formulated to realize the operational objectives. Typical examples of **control objectives** are: let the dissolved oxygen follow a changing desired value and keep the actual respiration rate at 42 mg l^{-1} h^{-1}. These can be implemented directly in control strategies; see also Chapter 5.

As suggested above, respiration rate itself can be used as a controlled variable. For example, the actual or endogenous rate can be maintained at a certain value by manipulating some process variable, or the measurement can be used to indicate disturbances or activate an alarm. However, respirometry often is used to extract information with a particular biological significance from the measurements (see Chapter 4). In these cases it is not respiration rate itself but another variable that is the controlled variable. Although specifying these two approaches is not based on rigorous fundamental differences it may be helpful in realizing that respirometry-based control is not restricted to controlling the respiration rate of activated sludge.

2. Fundamentals of respiration

2.1 Biochemical background

Strictly, in biochemical terms, **respiration** is the adenosine triphosphate (ATP)-generating metabolic process in which either organic or inorganic compounds serve as electron donor and inorganic compounds such as O_2, NO_2^-, NO_3^- and SO_4^{2-} serve as the ultimate electron acceptor. If oxygen is the ultimate electron acceptor, the process is called **aerobic respiration**. ATP is generated as electrons removed from the substrate are transferred along the **electron transport chain** from one metabolic carrier to the next and, ultimately, to oxygen. In this way, the biomass converts the energy of intramolecular bonds in the substrate to the high-energy phosphate bonds of ATP. The energy then is used to synthesize the various molecular components required for cell growth and reproduction. The overall process of aerobic respiration by heterotrophic biomass is depicted schematically in Figure 2.1. **Heterotrophic biomass** (including not only bacteria and their storage materials, but also protozoa and other higher organisms), uses substrate consisting of carbonaceous material. Only a portion $(1 - Y_H)$ of the consumed organic substrate is oxidized to provide energy. The remainder of the substrate molecules (the yield, Y_H) is reorganized into new cell mass. Typically about half of the substrate (on a weight/weight basis) is converted into new biomass.

Carbonaceous substrate removal is not the only oxygen-consuming process. In addition, oxygen is consumed in other bacterial processes such as the oxidation of inorganic compounds by nitrifiers and other autotrophic bacteria, and specific microbial oxidation reactions catalysed by oxidases and mono-oxygenases.

Nitrifying bacteria include only a minor part of the substrate ammonia into new biomass: most of the substrate is oxidized for energy production. These autotrophic bacteria use dissolved carbon dioxide as a carbon source for new biomass. In comparison with heterotrophic biomass, nitrifiers need more oxygen for their growth. Nitrification occurs in two steps: the oxidation of ammonia to nitrite and the oxidation of nitrite to nitrate.

In addition to the oxygen consumption by heterotrophic and nitrifying biomass there are some other biological processes that can contribute to the respiration of activated sludge. Like nitrifiers, the autotrophic **sulphur bacteria** and **iron bacteria** utilize inorganic compounds instead of organic matter to obtain energy, and use carbon dioxide or carbonate as a carbon source. Sulphur bacteria are able to oxidize hydrogen sulphide (or other reduced sulphur compounds) to sulphuric acid. Iron bacteria oxidize inorganic ferrous iron to the ferric form to obtain energy.

Finally, some inorganic electron donors such as ferrous iron and sulphide can be chemically oxidized with oxygen and contribute to the observed respiration of biomass.

All oxygen-consuming processes contribute to the observed total respiration rate of the biomass. Respirometry is usually intended to measure only biological oxygen consumption and sometimes an attempt is made to distinguish between different biological processes such as heterotrophic substrate removal and nitrification. However, in many cases it is difficult to distinguish between specific microbial processes and to identify chemical oxygen consumption.

2.2 Modelling respiration

Modelling is important for the design and control of the activated sludge process, as well as for understanding the basics of respiration. In the **traditional modelling approach**, respiration is associated with the growth and decay of microorganisms. In the **death–regeneration approach**, adopted in the IAWQ Activated Sludge Model No. 1, respiration is associated only with the aerobic growth of heterotrophic and nitrifying biomass. Figure 2.2 schematically shows the main processes for heterotrophic growth and biodegradation for the two approaches.

Both approaches describe growth of biomass (X_H) as a process in which oxygen is consumed. However, the traditional approach considers biomass decay as an additional oxygen-consuming process, in which decaying biomass is oxidized while inert matter (X_P) is formed. The model implies that, when the activated sludge has run

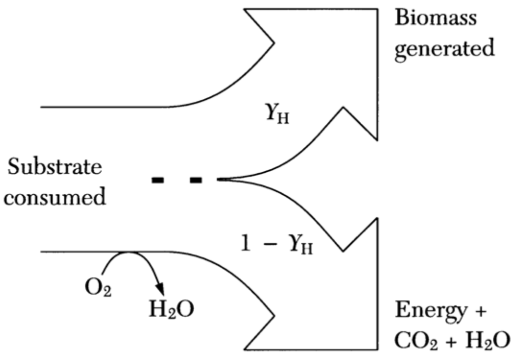


Figure 2.1. Schematic representation of aerobic respiration by heterotrophic biomass.

out of readily biodegradable substrate (S_S) and slowly biodegradable matter (X_S) from the wastewater, the remaining oxygen consumption is associated with biomass decay only.

Under the death–regeneration approach, decaying biomass is split into two fractions: inert matter and slowly biodegradable matter. The latter is subsequently hydrolysed into readily biodegradable substrate. This process does not involve any consumption of oxygen (or another electron acceptor). The death–regeneration model implies that, even when all the substrate originating from the wastewater has been oxidized, there remains an oxygen consumption associated with the growth on substrate released from decay and hydrolysis. The amount of new biomass formed from released substrate is always less than the amount of biomass lost.

Both models imply that if biomass is left on its own without input of biodegradable matter from wastewater, the respiration rate will gradually decrease until all the biomass has decayed. The respiration rate during this process is called the **endogenous respiration rate**. The endogenous respiration rate of activated sludge can be defined in operational terms as the oxygen consumption rate in the absence of substrate from external sources. By this definition, endogenous respiration includes not only the decay of bacteria (and concomitant growth in the case of death–regeneration) but also oxygen consumption by protozoa. Note that in the microbiological literature the maintenance concept is also used as another description of microbial behaviour. In this concept external substrate is oxidized to maintain the biomass in its current state. No new biomass is produced, distinguishing maintenance from growth, and substrate is oxidized only for energy generation. A consensus is growing that from a modelling and measuring point of view both maintenance and endogenous concepts are able to represent this specific process behaviour. The endogenous respiration rate is practically independent of the substrate concentration and is therefore indicative of the concentration of active biomass.

In the activated sludge process there is usually a continuous input of biodegradable material from the influent. This results in a net growth of biomass and an associated respiration rate that is higher than the endogenous rate. This **actual respiration rate** is a function of the concentration of biodegradable matter in the aeration tank, which is in turn the net result of three processes: input from the influent, loss via the effluent and biodegradation. It is obvious that this balance is disturbed when activated sludge is sampled from the aeration tank and hence that the respiration rate measured in the sample is likely to be biased to lower values.

If the concentration of biodegradable matter is very high, the biomass will grow at its maximum rate and the rate of oxygen consumption will approximate its maximum value: the **maximum respiration rate**. In the real world of an activated sludge plant treating sewage, respiration is the result of the oxidation of multiple substrates by a heterogeneous population of microorganisms. This means that the true maximum respiration rate is reached only if all the individual substrates are present in excess. In an activated sludge plant this condition is not very likely to occur. In a well-designed respirometric experiment, however, the appropriate condition for measurement of the maximum

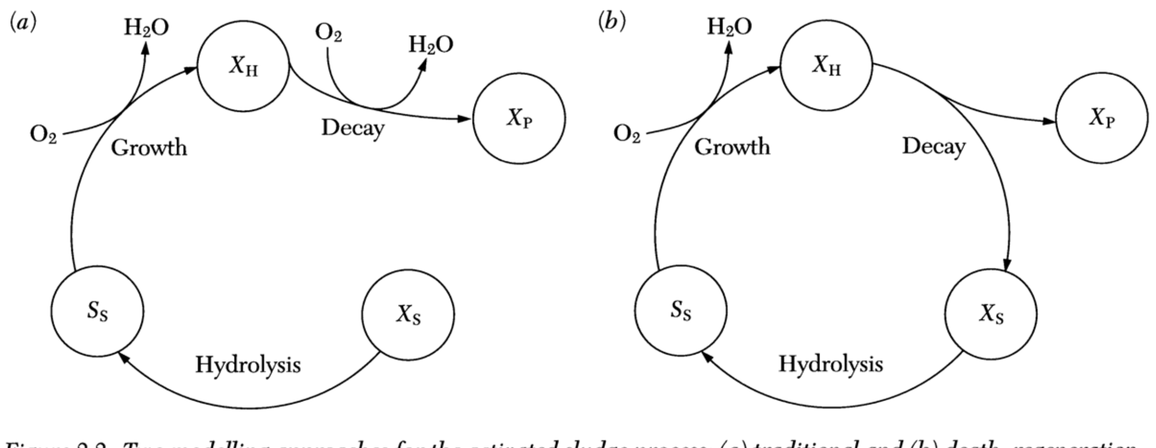


Figure 2.2. Two modelling approaches for the activated sludge process: (a) traditional and (b) death–regeneration.

respiration rate can be created and the measurement can be used for model identification. Like the endogenous respiration rate, the maximum respiration rate is practically independent of substrate concentration and is therefore indicative of the active biomass concentration.

By using the model concepts depicted in Figure 2.1, respiration rate can be expressed mathematically in terms of growth and decay. The traditional model (growth and decay of nitrifiers included) is

$$r_O = \frac{1-Y_H}{Y_H}\mu_H(S_S, S_O)X_H + \frac{4.57-Y_A}{Y_A}\mu_A(S_{NH}, S_O)X_A + [1-f'_P] \times [b'_H(S_O)X_H + b_A(S_O)X_A] \quad (2.1)$$

and the death–regeneration model is

$$r_O = \frac{1-Y_H}{Y_H}\mu_H(S_S, S_O)X_H + \frac{4.57-Y_A}{Y_A}\mu_A(S_{NH}, S_O)X_A. \quad (2.2)$$

The specific growth rates $\mu_H(S_S, S_O)$ and $\mu_A(S_{NH}, S_O)$ are dependent on the substrate concentrations S_S and S_{NH}, respectively, and on the dissolved oxygen concentration S_O:

$$\mu_H(S_S, S_O) = \frac{\mu_{mH}S_S}{K_S + S_S}\frac{S_O}{K_{OH} + S_O}, \quad (2.3)$$

$$\mu_A(S_{NH}, S_O) = \frac{\mu_{mA}S_{NH}}{K_{NH} + S_{NH}}\frac{S_O}{K_{OA} + S_O}. \quad (2.4)$$

In the traditional model the decay rates $b'_H(S_O)$ and $b_A(S_O)$ are dependent only on the dissolved oxygen concentration:

$$b'_H(S_O) = b'_{mH}\frac{S_O}{K_{OH} + S_O}, \quad (2.5)$$

$$b_A(S_O) = b_{mA}\frac{S_O}{K_{OA} + S_O}. \quad (2.6)$$

It is seen from Equation 2.1 that the respiration rate is governed by the growth of both heterotrophs and nitrifiers, and the decay of both types of biomass. At high substrate concentrations (S_S, S_{NH} and S_O) the first and second terms approach saturation and so does the respiration rate (maximum rate). If all the substrate is oxidized, the first and second terms become zero and the lower (endogenous) respiration rate is governed by the biomass concentration. In the death–regeneration model (Equation 2.2), even when external substrate is absent, the concentration will never approach zero because substrate is regenerated from decay and subsequent hydrolysis (see Figure 2.2). In nitrifying biomass part of the nitrogen released from decay will be nitrified during endogenous respiration.

Note that in the description above, heterotrophic growth is associated with only one substrate (S_S). In other model approaches, heterotrophs can grow on more substrates with concomitant oxygen consumption. In addition, nitrification can be explicitly modelled as a two-step process: oxidation of ammonium to nitrite and subsequent oxidation of nitrite to nitrate.

2.3 Linking respirometry to substrate removal and growth

In wastewater treatment, waste removal and biomass activity are important processes that need to be monitored for good process control. On a cellular level these correspond to substrate conversion and biomass growth. It was shown above that respiration is linked to these key metabolic processes that take place in the cell. Because it is not possible to measure respiration rates within the biomass itself, we have to resort to a measurement of the oxygen uptake rate from the bulk into the biomass. However, because a rate measurement is made, (i.e. time is involved), the dynamics of the dissolved oxygen concentration are important. In other words, it is necessary to assess the dissolved oxygen accumulation (positive or negative) in the bulk liquid, and also the inputs and outputs. We might also have to consider the removal of oxygen through chemical oxidation reactions and eliminate this to calculate biological oxygen consumption. Alternatively, as oxygen is typically supplied from the gas phase, the disappearance of gaseous oxygen can also be measured and related to biomass growth and substrate removal. Obviously, this additional phase complicates the interpretation of the measured gaseous oxygen uptake rate, because

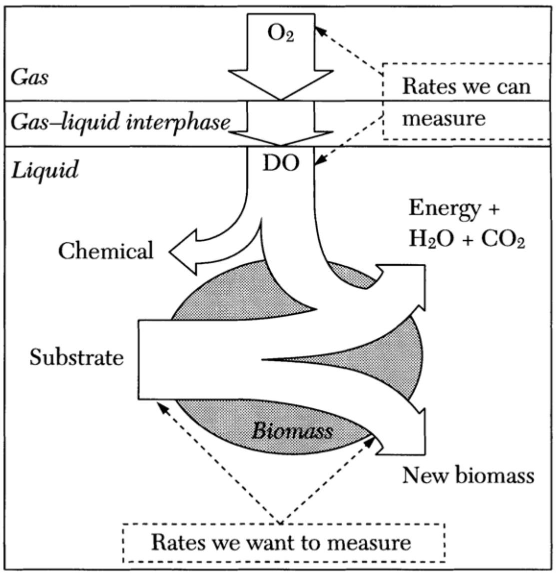


Figure 2.3. Relationship between respiration, substrate utilization and growth.

the interphase transport process should be characterized.

Figure 2.3 illustrates that linking respirometry to substrate removal and growth might involve three phases (biomass, liquid phase and gas phase) and that respiration rates can be assessed from either the liquid phase or the gas phase.

3. Measuring principles

3.1 Introduction

In the description of respirometers there is, probably more than with any other measuring instrument, confusion about operating principles. Operation is characterized with terms such as in-line, on-line, in-situ, continuous, semi-continuous and batch. The reason is that respirometers are often small activated sludge reactors by themselves, of which the operation is more open to the users allowing them to make their own interpretation of the measuring results. The characterization can pertain to the operation of the respirometer or to the way in which it interacts with the treatment plant.

A **respirometer** is an instrument for measurement of the respiration rate; that is, the mass of oxygen consumed per (unit of volume and) unit of time. Instruments that are specifically designed to measure biochemical oxygen demand are sometimes called respirometers too. However, these instruments often cannot provide rates (measurements expressed per unit of time) without major modifications in operation and calculation procedures. Therefore they should be denoted **BOD meters**. The same holds for respirometry-based **toxicity meters**, which are designed to provide a measure of toxicity. Some instruments are capable to operate in different modes in such a way that they comprise all three meters above.

3.2 General principle

The respiration rate is usually measured with a respirometer. Respirometers range from a simple, manually operated bottle equipped with a dissolved oxygen (DO) sensor to complicated instruments that operate fully automatically. In some cases the aeration tank of the treatment plant itself can serve as a respirometer. Except for the latter case, a feature common to all respirometers is a reactor, separated from the activated sludge tank, where different components (biomass, substrate, etc.) are brought together. The operation of all respirometers involves some technique for assessing the rate at which the biomass takes up DO from the liquid. Many techniques have been developed in the past. However, the Task Group found that all measuring techniques for the respiration rate can be classified into only eight basic principles according to two criteria: (1) the phase where oxygen concentration is measured (gas or liquid, G and L, respectively) and (2) whether or not there is input and output of liquid and gas (flowing or static, F and S, respectively). The operation of all existing respirometers can be explained in terms of these criteria. Figure 3.1 shows a generic scheme of a respirometer. Note that the gas phase also includes bubbles dispersed in the liquid phase. In the subsequent sections, the principles will be discussed according to the above criteria. We shall not discuss the usefulness of the different measuring techniques because we believe that any technique has its merits, depending on the specific application, provided that the correct measuring conditions are satisfied.

3.3 Principles based on measuring oxygen in the liquid phase

Most techniques based on the measurement of oxygen in the liquid phase use an electrochemical DO sensor. The DO sensor generally consists of two or three electrodes in an internal electrolyte solution separated from the liquid by a semipermeable membrane. Dissolved oxygen molecules diffuse from the liquid through the membrane into the internal solution. The molecules are reduced on the cathode, generating an electrical current. This current is proportional to the diffusion rate of the oxygen molecules through the membrane, which in turn is proportional to the DO concentration in the solution. The relationship between electrical current and DO concentration is established by calibrating the DO sensor. For a DO sensor, water-saturated air is equivalent to oxygen-saturated water. This is used to calibrate the DO sensor in water-saturated air at 100% DO, i.e. saturation DO concentration in the liquid. A reliable respiration rate measurement is possible only if the DO sensor is correctly calibrated and if a number of environmental variables, such as temperature and pressure, are accounted for. DO sensors also have a response time that must be accounted for in some respirometric set-ups.

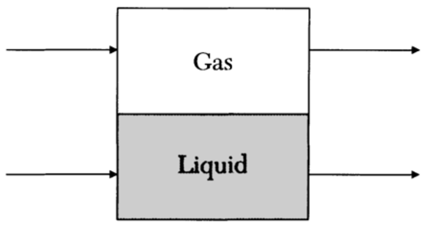


Figure 3.1. Generic scheme of a respirometer.

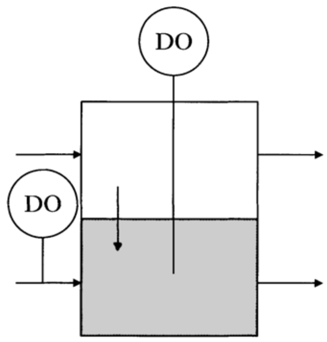


Figure 3.2. Liquid-phase principle; flowing gas, flowing liquid (LFF).

Respirometers that are based on measuring DO concentration in the liquid phase use a DO mass balance over the liquid phase. Consider a system consisting of a liquid phase, containing biomass, and a gas phase both being ideally mixed and having an input and output (Figure 3.2). It is assumed that the DO concentration in the liquid phase can be measured. The DO mass balance over the liquid phase is:

$$\frac{d(V_L S_O)}{dt} = Q_{in} S_{O,in} - Q_{out} S_O + V_L K_L a (S_O^* - S_O) - V_L r_O, \quad (3.1)$$

where:

S_O = DO concentration in the liquid phase
S_O^* = saturation DO concentration in the liquid phase
$S_{O,in}$ = DO concentration in the liquid phase entering the system
$K_L a$ = oxygen mass transfer coefficient (based on liquid volume)
Q_{in} = flow rate of the liquid entering the system
Q_{out} = flow rate of the liquid leaving the system
r_O = respiration rate of the biomass in the liquid
V_L = volume of the liquid phase.

Notice that, because it is a mass balance over the liquid phase, Equation 3.1 does not contain gas flow terms. The first and second term on the right-hand side represent advective flow of DO in the input and output liquid streams. In most systems Q_{in} and Q_{out} will be equal, so that the liquid volume is constant. The third term describes the mass transfer of oxygen from the gas phase to the liquid phase. The last term contains the respiration rate to be derived from the mass balance. S_O must therefore be measured and all other coefficients be known or neglected. In practice, the determination of r_O can be simplified in several ways. In what follows it is assumed that the liquid volume is constant, so that the terms in Equation 3.1 can be divided by V_L. It should be noted that the volume V_L refers to the actual liquid volume plus the volume of any gas bubbles dispersed in the liquid phase. That is, $K_L a$ is defined on the basis of the dispersed liquid volume. In diffused air systems with high gas flow rates, the hold-up of gas bubbles in the liquid phase can be significant. It is therefore important to clarify whether $K_L a$ is defined with respect to liquid volume only or to the dispersed liquid volume.

3.3.1 Static gas, static liquid (LSS)

One approach is to use a method without liquid flow and oxygen mass transfer (Figure 3.3). Then the first three terms on the right-hand side of Equation 3.1 fall away and the mass balance reduces to:

$$dS_O/dt = -r_O. \quad (3.2)$$

Hence, to obtain the respiration rate only the differential term has to be determined. This can be done by measuring the decrease in DO as a function of time due to respiration, which is equivalent to approximating the differential term with a finite difference term: $\Delta S_O/\Delta t = -r_O$. Typical of this principle is that the DO may become exhausted after some time, so that for continued measurement of r_O reaeration is needed to bring the DO concentration back to a higher level. DO and substrate are limiting the respiration (see Equations 2.1 and 2.2) when their concentrations become too low, causing a nonlinear DO decrease and complicating the assessment of the differential term. Note that in Figure 3.3 there is a gas phase. However, there is no mass transfer from the gas phase into the liquid phase. In practice, to prevent transfer of oxygen across the gas/liquid interface, the gas phase may be absent. The procedure for the determination of r_O according to *Standard Methods* (19th edn, American Public Health Association, Washington, D.C. (1995)) is based on this principle. The principle is often used for manually measuring r_O but it is also implemented in automatic respirometers that sample activated sludge from an aeration basin and do one or more measurements of the DO decrease.

3.3.2 Flowing gas, static liquid (LFS)

The disadvantage of the need for reaerations can be eliminated by continuously aerating the biomass. Then, the oxygen mass transfer term

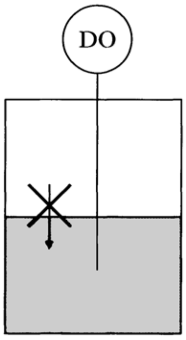


Figure 3.3. Liquid-phase principle; static (no) gas, static liquid (LSS).

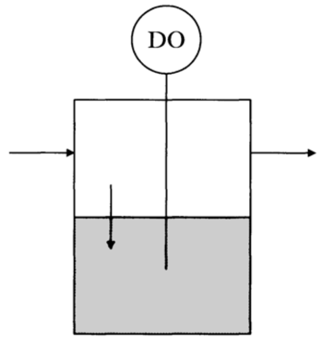


Figure 3.4. Liquid-phase principle; flowing gas, static liquid (LFS).

$K_La(S_O^* - S_O)$ must be included in the mass balance (Equation 3.2):

$$dS_O/dt = K_La(S_O^* - S_O) - r_O. \tag{3.3}$$

To obtain r_O both the differential term and the mass transfer term must be determined. To calculate the latter, the mass transfer coefficient (K_La) and the DO saturation concentration (S_O^*) must be known. These coefficients have to be determined regularly because they depend on environmental conditions such as temperature, barometric pressure and the properties of the liquid. The simplest approach is to determine these by using separate reaeration tests and look-up tables. Another approach is to estimate the coefficients from the dynamics of the DO concentration response (for example to changes in the aeration intensity) by applying parameter estimation techniques. The advantage of the latter method is that the values of the aeration coefficients can be updated relatively easily. This respirometric principle allows the measurement of r_O at a nearly constant DO concentration, thereby eliminating the dependency of r_O on the DO concentration (provided that DO $\gg$ 0 mg l^{-1}). This principle can be implemented in a separate respirometer or directly in a batch aeration tank. Note that, whereas Figure 3.4 shows an input and an output on the gas phase, there is no gas flow term in Equation 3.3. There is no need to consider gas flow terms provided that S_O^* is known or determined (see Section 3.4).

3.3.3 Static gas, flowing liquid (LSF)

Repetitive aeration or estimation of oxygen transfer coefficients, as with the above principles, can be avoided when liquid with a high enough input DO concentration flows continuously through a closed completely mixed cell without gas phase (Figure 3.5). The liquid flow terms now have to be included in the mass balance (Equation 3.2).

$$\frac{dS_O}{dt} = \frac{Q_{in}}{V_L} S_{O,in} - \frac{Q_{out}}{V_L} S_O - r_O. \tag{3.4}$$

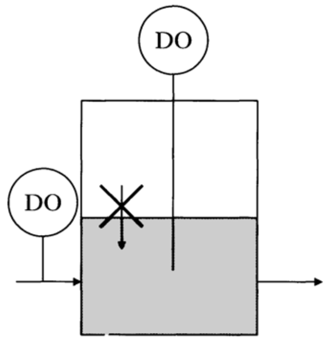


Figure 3.5. Liquid-phase principle; static (no) gas, flowing liquid (LSF).

Both DO concentrations, $S_{O,in}$ and S_O, must be measured continuously to allow calculation of r_O. In a respirometer Q_{in} and V_L are instrument constants and are therefore assumed known or calibrated. This principle is in fact the continuous counterpart of that explained in Equation 3.2, and it is thus also sensitive to the effect of substrate and DO limitation. However, the effect of limiting substrate can be eliminated by the continuous supply of substrate (wastewater) and DO to the respiration cell.

The principle described above and other principles with liquid flow are also applicable to a plug flow type cell. However, the exact respiration rate in the cell cannot be obtained from Equation 3.4 because of the spatial distribution of r_O and S_O along the plug flow cell. In this case respiration rate can be calculated from the DO concentration in the liquid entering the cell and that in the liquid leaving the cell, obviously resulting in a measurement delay equal to the hydraulic residence time of the cell.

3.3.4 Flowing gas, flowing liquid (LFF)

Without the above simplifications the full mass balance (Equation 3.1) holds for the principle depicted in Figure 3.2. To obtain respiration rate measurements with this principle, a combination of the approaches mentioned for the above simplified principles is required. For instance, the flow rates and the inlet oxygen concentrations must be measured, whereas the coefficients K_La and S_O^* must be assessed, for

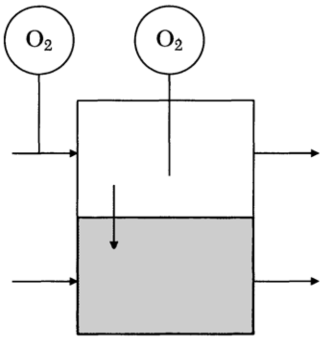


Figure 3.6. Gas-phase principle; flowing gas, flowing liquid (GFF).

example by estimating these from the dynamics of the DO concentration.

3.4 Principles based on measuring oxygen in the gas phase

Respirometric techniques based on measuring gaseous oxygen always deal with two phases: a liquid phase containing the respiring biomass and a gas phase in which the oxygen measurement takes place. The main reason for measuring in the gas phase is to overcome difficulties associated with interfering contaminants that are common in the liquid phase (for example the formation of sludge film on the sensor). Gaseous oxygen is measured by physical methods such as the paramagnetic method, or gasometric methods. Oxygen is one of the few gases that show paramagnetic characteristics, so it can be measured quantitatively in a gaseous mixture by using the paramagnetic method. The method is based on the change in a magnetic field as a result of the presence of oxygen; this change is proportional to the concentration of gaseous oxygen.

Gasometric methods measure changes in the concentration of gaseous oxygen. According to the ideal gas law $PV = nRT$, these can be derived from changes in the pressure (if volume is kept constant; **manometric method**) or changes in the volume (if pressure is kept constant; **volumetric method**). These methods are typically applied to closed measuring systems (no input and output streams), which may provoke a need for reaerations and thus a temporary interruption of the measurements. This limits the possibility for continued monitoring of the respiration rate. However, interruptions because of reaerations are not needed if the consumed oxygen is replenished at a known rate, for example by supplying pure oxygen from a reservoir or by using electrolysis. The rate at which oxygen is supplied is then equivalent to the biological respiration rate (assuming infinitely fast mass transfer to the liquid). Because carbon dioxide is released from the liquid phase as a result of the biological activity, this gas has to be removed from the gas phase to avoid interference with the oxygen measurement. In practice this is done by using alkali to chemically absorb the carbon dioxide produced.

Respirometric principles based on measuring gaseous oxygen also use oxygen mass balances to derive the respiration rate. However, in addition to the mass balance on the liquid phase (Equation 3.1), a balance on the (ideally mixed) gas phase must be considered (Figure 3.6):

$$\frac{\mathrm{d}(V_G C_O)}{\mathrm{d}t} = F_{in} C_{O,\,in} - F_{out} C_O - V_L K_L a (S_O^* - S_O), \tag{3.5}$$

where:

C_O = O_2 concentration in the gas phase
$C_{O,\,in}$ = O_2 concentration in the gas entering the system
F_{in} = flow rate of the gas entering the system
F_{out} = flow rate of the gas leaving the system
V_G = volume of the gas phase.

The term $V_L K_L a (S_O^* - S_O)$ represents the mass transfer rate of oxygen from the gas phase to the liquid phase, and it is the connection between the two phases. From mass balances (Equations 3.1 and 3.5) it follows that, to calculate r_O, C_O must be measured (directly or by using the gas law; see above) and knowledge of S_O is required. However, S_O is not measured in the gas-phase principles. In these respirometric principles it is assumed that the oxygen concentrations in the gas and liquid phases are in equilibrium; that is, mass transfer is sufficiently fast ($K_L a \to \infty$), so that $S_O \approx S_O^*$. Because, by definition, the saturation DO concentration is proportional to the O_2 concentration in the gas phase,

$$S_O^* = H C_O, \tag{3.6}$$

it is reasonable to state that

$$S_O = H C_O, \quad \text{and} \tag{3.7}$$

$$\frac{\mathrm{d}S_O}{\mathrm{d}t} = H \frac{\mathrm{d}C_O}{\mathrm{d}t}. \tag{3.8}$$

Hence, the measurement in the gas phase is a good representation of the condition in the liquid phase, provided that the proportionality (Henry) constant H is known, for example from calibration or tables, and the mass transfer coefficient is high. Especially in full-scale situations where the aeration tank is used as a respirometer, the validity of this equilibrium assumption should be critically evaluated.

3.4.1 Static gas, static liquid (GSS)

The simplest gas-phase technique for measuring respiration rate is based on a static liquid phase and a static gas phase; that is, no input and

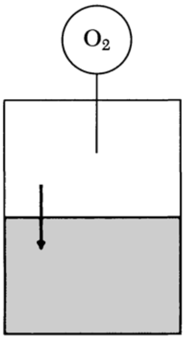


Figure 3.7. Gas-phase principle; static gas, static liquid (GSS).

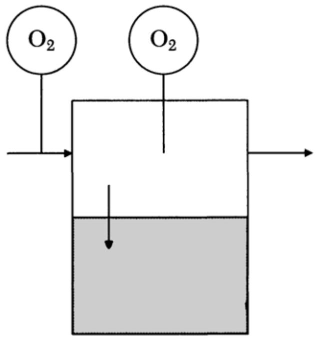


Figure 3.8. Gas-phase principle; flowing gas, static liquid (GFS).

output (Figure 3.7). In addition to the DO mass balance on the liquid phase, an oxygen mass balance on the gas phase must be considered:

$$\frac{dS_O}{dt} = K_La(S_O^* - S_O) - r_O, \quad (3.9)$$

$$\frac{d(V_GC_O)}{dt} = -V_LK_La(S_O^* - S_O). \quad (3.10)$$

Hence, to calculate r_O, the change in the oxygen concentration in the gas phase, dC_O/dt, must be measured and knowledge of dS_O/dt is required (see above). dC_O/dt can be measured by using an oxygen sensor. If a gasometric method is used, dC_O/dt is related to the change in volume or the change in pressure (see above).

With this principle the same restriction as with the simplest DO-based principle exists: when the oxygen becomes exhausted it must be replenished by, for instance, venting the gas phase to continue the measurement of r_O.

3.4.2 Flowing gas, static liquid (GFS)

Another technique is based on a flowing gas phase, i.e. the biomass is continuously aerated with air (or pure oxygen) so that the presence of sufficient oxygen is ensured (Figure 3.8). In comparison with Equation 3.10 two transport terms must be included in the mass balance on the gas phase:

$$\frac{dS_O}{dt} = K_La(S_O^* - S_O) - r_O, \quad (3.11)$$

$$\frac{d(V_GC_O)}{dt} = F_{in}C_{O,in} - F_{out}C_O - V_LK_La(S_O^* - S_O). \quad (3.12)$$

To allow calculation of r_O, the gas flow rates, F_{in} and F_{out}, and the oxygen concentrations in the input and output streams, $C_{O,in}$ and C_O, must be known in addition to the variables of the previous technique. Of these, C_O is usually measured and the others are set or known. A gasometric method is not evident here, and the measurement of C_O is made, for example, by the paramagnetic method.

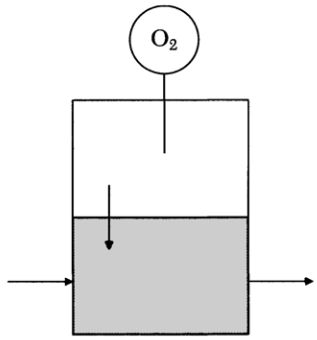


Figure 3.9. Gas-phase principle; static gas, flowing liquid (GSF).

3.4.3 Static gas, flowing liquid (GSF)

Implementations of the gas-phase principle with static gas and flowing liquid have not been found in literature and practice so far. With this principle the (change in) oxygen concentration in the liquid phase must be determined, for example as described above, in addition to the oxygen measurement in the gas phase:

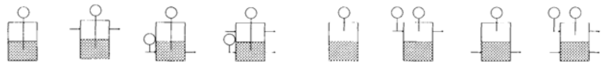
$$\frac{dS_O}{dt} = \frac{Q_{in}}{V_L}S_{O,in} - \frac{Q_{out}}{V_L}S_O + K_La(S_O^* - S_O) - r_O, \quad (3.13)$$

$$\frac{d(V_GC_O)}{dt} = -V_LK_La(S_O^* - S_O). \quad (3.14)$$

3.4.4 Flowing gas, flowing liquid (GFF)

The gas-phase principle can also be applied to a full-scale aeration tank. In this case there are liquid input and output streams for the tank, and transport terms must be added to the mass balance on the liquid phase (Equation 3.1). The assumption on proportionality between C_O and S_O (Equation 3.7) becomes more critical because, in addition, also the liquid outflow term depends on it. Additional measurement of dissolved oxygen can then be useful for a correct

Table 3.1. Overview of principles of measuring respiration rate

			Measurement in liquid phase				Measurement in gas phase			
		Respirometric principle … 								
	Process	Coefficient	LSS	LFS	LSF	LFF	GSS	GFS	GSF	GFF
Liquid-phase balance	Respiration	$V_L r_O$	–1	–1	–1	–1	–1	–1	–1	–1
	Dissolved oxygen accumulation	$\frac{d(V_L S_O)}{dt}$	–1	–1	–1	–1	–1	–1	–1	–1
	Liquid flow	$Q_{in}S_{O,in} - Q_{out}S_O$			1	1			1	1
	Gas exchange	$V_L K_L a(S_O^* - S_O)$		1		1	1	1	1	1
Gas-phase balance	Gaseous oxygen accumulation	$\frac{d(V_G C_O)}{dt}$					–1	–1	–1	–1
	Gas flow	$F_{in}C_{O,in} - F_{out}C_O$						1		1
	Gas exchange	$V_L K_L a(S_O^* - S_O)$					–1	–1	–1	–1

assessment of respiration rate. The technique would then no longer be a pure gas-phase principle. Note, however, that in general combining L and G principles can lead to more reliable measurements of respiration rate.

3.5 Summary

Table 3.1 summarizes the measuring principles. The first column contains the names of the mass balance terms, and the second the mathematical equivalents. The succeeding columns list the respirometric principles, the first four being liquid-phase principles, and the others being gas-phase principles. The mass balances for each principle are formed by multiplying the mathematical terms by the coefficients in the column of the appropriate principle. The sum of all terms must equal zero.

4. Measured and deduced variables

4.1 Introduction

Like any other measuring device, a respirometer can be considered to be a sensor. In fact, a respirometer can be constructed in such a compact and physically manageable way that it can easily be regarded as one unit consisting of a number of subunits, such as sampling port, sensing element and transducer, that are concealed from the user. The user does not easily see the internal structure of the respirometer and, in fact, this is not necessary for operating the instrument.

In contrast, it can be conceptually difficult to consider a respirometer as a sensor because it contains a (mini) reactor where experiments are done by combining different components or process streams, and in which the measurement conditions generally have a very large influence on the measurement results. Even the respirometer's operating principle itself and its concomitant measurement condition (for example, no oxygen mass transfer) can have an effect on the respiration rate of the biomass.

No matter where a respirometer is located, the conditions in the respirometer are decisive for the measurement results. Therefore, in this report these **measurement conditions**, not the measurement location, are specified as important characteristics for any measured respiration rate. In practice, however, the measurement conditions prevailing during respirometric experiments are not always clearly communicated.

In process operation, control and research a biological interpretation is sought for the measured respiration rate. The respirometric data are therefore frequently converted to deduced variables that better characterize the biology of activated sludge. Again, the variables that can be deduced from the measured respiration rate depend on the measurement conditions. This chapter discusses possible deduced variables.

4.2 Measured respiration rates

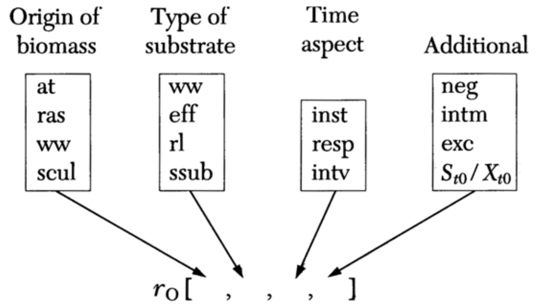
Most measured variables do not need additional information for interpretation (for example, dissolved oxygen or nitrate concentration). For respirometry this is not so. A respiration rate value or a percentage inhibition calculated from respiration rate measurements cannot be interpreted without additional information about some measurement attributes. The Task Group found that at least three attributes must be specified to interpret respiration rate measurements: (1) biomass source, (2) type of substrate and (3) time aspect (Figure 4.1). Some examples are given below for these attributes to indicate the diversity of respiration rates that can be obtained from respirometers.

4.2.1 Biomass

Several sources of respirometer biomass exist: aeration tank, return activated sludge, wastewater from the treatment plant being monitored. Although the choice of a biomass sampling point for a completely mixed aeration tank is trivial, for other reactor types the location from which the sludge is obtained (beginning, end, or which compartment) has a critical bearing on the measurement condition. Indeed, the state of the biomass itself and its environment (for example pH, dissolved oxygen and substrate levels) will partly determine the result of the respirometric measurement. The conditions at the sampling point are therefore very important. The source of biomass also could be a specific culture grown separately, possibly on sewage or a synthetic substrate.

Activated sludge sampled from the aeration tank often contains dissolved oxygen and a varying and mostly unknown quantity of substrate. Return activated sludge has a higher biomass concentration and often low dissolved oxygen and substrate concentrations. In contrast, the concentration of substrate is high and that of biomass is low when the sample comes from sewage, whereas dissolved oxygen is likely to be absent.

Biomass of a specific culture is grown separately from the activated sludge on sewage or a different substrate. It therefore resembles more or less the biomass in the treatment plant but has the advantage that the characteristics of the culture are better known. Because of the limited production rate of biomass, it is mostly kept in the measuring system by growing it on a carrier and the culture is thus an inherent part of the respirometer.



at	Activated sludge tank
at*k*	*k*th compartment of plug flow tank
ras	Return activated sludge
ww	Wastewater
scul	Specific culture
eff	Effluent
rl	Return liquor
ssub	Specific substrate
inst	Instantaneous
resp	Respirogram
intv	Interval
neg	Negligible
intm	Intermediate
exc	Excess substrate
S_{t0}/X_{t0}	Initial substrate-to-biomass ratio

Figure 4.1. Nomenclature of respiration rate (see text for explanation).

4.2.2 Substrate

Four substrate types have been considered in respirometry: wastewater (raw or settled), effluent, return liquors from the sludge treatment, and specific substrates. A specific substrate such as acetate or ammonium can be used to mimic the oxidation of (a) particular (group of) component(s) in wastewater.

4.2.3 Time aspect

Like many variables, respiration rate is a function of time. The measurement obtained with a respirometer can be executed in three modes: instantaneous, respirogram and interval. An instantaneous measurement assumes that the elapsed time between onset of the experiment and respiration rate measurement is zero, so that the initial condition is measured. A respirogram means that the respiration rate in the respirometer is tracked for some time to obtain a time series of respiration rate values. An interval type measurement denotes a (single) relevant respiration rate measurement after a specified time interval in the respirometer.

When sludge is transferred from an activated sludge tank into a respirometer the respiration rate in the meter is still a function of time (although not in the time frame of the treatment process but in a new time frame: that of the measurement) because of, for example, a change in the substrate concentration. If the rate is measured immediately, an instantaneous measurement is obtained that can closely reflect the condition in the activated sludge tank. Continuing the measurement yields a time course, i.e. a respirogram, which provides information on the biomass and substrate characteristics. After a predetermined or variable time interval the substrate might be exhausted, and the endogenous respiration rate is measured. At this time (or immediately after sampling) an extra amount of substrate can be added to obtain a respirogram with sufficient dynamics to extract information about biomass and substrate characteristics.

4.2.4 Additional attributes

The concentration of substrate, like the time aspect, is an important environmental condition in the respirometer reactor that is crucial for the information content of the measurement results obtained. Three levels of substrate concentration can be defined: negligible, intermediate and excess. Negligible substrate levels can be obtained when no substrate is added intentionally or sufficient removal of substrate is guaranteed before the onset of the experiment. It is expected or intended that the remaining substrate has no effect on the measured respiration rate. An intermediate level might be obtained if there is still a significant amount of substrate left in the sludge at the moment of sampling, or if a specific amount of substrate is brought into the respirometer together with the sludge. A condition with excess substrate is characterized by the fact that a small change in substrate concentration has no effect on the measured respiration rate. For some variables deduced from respiration rate data, the initial substrate-to-biomass ratio S_{t0}/X_{t0} at the onset can be crucial and should be reported.

In addition, specific components (e.g. allyl thiourea) that are not used as a substrate but act as an inhibitor for part of the biochemical processes can be brought into the respirometer. Other environmental conditions such as pH and temperature are also important for the measurement result. However, these factors are usually not a part of the measurement strategy. They are assumed to be similar to the conditions in the treatment plant and kept, or assumed, constant or of no influence on the result.

4.2.5 Nomenclature

In this report the respiration rate will be symbolically associated with the attributes presented above (Figure 4.1). Some examples are as follows. The respiration rate measured immediately after sampling from a completely mixed aeration tank, the actual respiration rate in the tank, would be represented as follows: r_O[at, –, inst]. The dash means that no substrate is added. If, after sampling, the sludge is aerated

Table 4.1. Selection of deduced variables obtained from respiration rate measurements

For explanation of nomenclature, see Figure 4.1. The wildcard '*' means that different biomass sources, substrate types and time aspects are possible.

Deduced variable	Respiration rates (and other measurements)	Method
R	r_O[*, *, *] (and X)	Arithmetic
BOD_{st}	r_O[*, *, resp]	Integration
	r_O[*, ww, inst]	Arithmetic
I	r_O[*, ww, inst, exc]	Comparison
t.t.e.	r_O[*, ww, resp]	Comparison
X	r_O[*, –, inst]	Arithmetic
	r_O[*, ssub, inst, exc]	Arithmetic
	r_O[*, ssub, resp]	Parameter estimation
B_X	r_O[at, ww, inst], r_O[ras, –, inst] (and Q_{in}, Q_{ras})	Arithmetic
$r_{NH, max}$	r_O[at, –, resp], r_O[at, ssub, resp]	Arithmetic
	r_O[at, ssub, resp, exe]	Parameter estimation
ASM parameters	r_O[*, ww, resp] (and X)	Parameter estimation
ASM components	r_O[*, ww, resp]	Parameter estimation
	r_O[at, ww, inst, exc], r_O[at, ww, inst], r_O[at, –, intv]	Arithmetic

for a prolonged time to measure endogenous respiration rate, one would write r_O[at, –, intv]. A respiration rate denoted r_O[at1, ww, resp] means the rate for sludge from the first compartment of an aeration tank in the presence of wastewater, measured for some time, in other words a respirogram. It is not the intention to use the attributes as a symbolic notation, for example in equations, but merely as a way of presenting and explaining measured respiration rates concisely.

4.3 Deduced variables

The respirometric measurement result (the raw respiration rate value obtained under specific conditions in the respirometer) is usually not used directly in a control strategy. It must first be converted to a deduced variable relevant in the control strategy. A **deduced variable** is defined as a variable that results from a calculation performed with one or more measured respiration rate values and possibly other measured variables. Many deduced variables have been proposed. In Table 4.1 a selection of deduced variables is presented, together with the respiration rate(s) from which the variable is deduced, the other measured variables used in the calculations, and the calculation method applied. For the calculation of some deduced variables different methods have been proposed.

Most often, simple **arithmetic** calculations involving different types of respiration rates or involving respiration rate and some other measurement lead to a deduced variable. For instance, the specific respiration rate R is calculated as respiration rate divided by the mixed liquor suspended solids concentration X.

A second type of calculation involves the use of an **integration** step; in other words, the area under a time course of respiration rates (respirogram) is calculated r_O[*, *, *]. (The wildcard '*' means that different biomass sources, substrate types or time aspects are possible.) This is used in one approach for assessment of the short-term BOD (BOD_{st}), a measure of the substrate concentration. An alternative, arithmetic, method for BOD_{st} calculation uses a Monod relationship between the instantaneous respiration rate with a wastewater sample r_O[at, ww, inst], and the wastewater BOD_{st}.

A third method used in deduced variable calculation consists of a **comparison** between respiration rates collected at different times or from different sources. For instance, the percentage inhibition (I) of a wastewater can be assessed from a comparison between maximum respiration rates before and after a toxicant entered the wastewater. Basically, by performing such comparisons the derivative of the maximum respiration rate with time is determined in a very simple way and the change in respiration rate is monitored. Another example of the application of comparison is in the assessment of the treatment time, defined as the time needed to reach endogenous respiration in a batch experiment (time to endogenous, t.t.e.). Obviously, this requires a comparison of the measured respiration rates with a predefined endogenous rate.

Finally, in recent years a number of sophisticated algorithms for **parameter estimation** have evolved for the deduction of relevant variables. Respirometry is increasingly used to assess the parameters and components of the IAWQ Activated Sludge Model No. 1. For instance, maximum growth rates and saturation coefficients of heterotrophs and nitrifiers, and the components in a wastewater, have been deduced from respirograms r_O[*, ww, resp]. For a specific growth rate, a measure of biomass concentration is needed.

It is beyond the scope of this report to explain the underlying mathematics, but basically the parameter estimation algorithms try to find parameter values (maximum growth rates, saturation coefficients, component concentrations, etc.) that lead to the smallest deviation between model predictions and measured respiration rates.

In an alternative, arithmetic, approach the carbonaceous component of the ASM No. 1 S_S has been calculated by using three different respiration rates with the same biomass and wastewater: r_O[at, ww, inst, exc], r_O[at, ww, inst] and r_O[at, –, intv].

5. Elementary control concepts

Control theory is not the primary topic of this chapter. However, some background must be given here to clarify the discussion in the next chapter. The elementary control concepts presented here are focused on respirometry-based control. Therefore, in some cases we shall divert somewhat from general control concepts if this improves the clarity.

5.1 Introduction

In the operation of wastewater treatment plants the **basic objective** is to keep the plant running, while meeting the effluent standards and minimizing costs. To achieve the basic objective a number of **operational objectives** have to be defined (Figure 5.1). Typical operational objectives are:

- grow the right biomass population
- maintain good mixing where appropriate
- maintain adequate loading
- maintain adequate aeration intensity
- favour good settling properties.

To be accomplished, these objectives cannot be implemented in control strategies at once. More specific **control objectives** therefore have to be formulated, such as:

- keep the respiration rate at 42 mg l^{-1} h^{-1}
- keep the mixed liquor suspended solids concentration at 3 g l^{-1}
- track the dissolved oxygen concentration according to a given pattern.

The correct choice of these objectives requires a thorough knowledge of the process including couplings between different process units. Note that each level of objectives is dealt with by a different group of professionals. The control objectives can be achieved by using manual or automatic controllers. The task of a simple controller is mostly emphasizing either set point tracking or disturbance rejection. Set point tracking means that the controller tries to let the **controlled variable** follow a changing desired value, the **set point**. Disturbance rejection means that the controller tries to compensate for the effects induced by external disturbances to keep the controlled variable on the set point value.

5.2 System description

The activated sludge process can be considered in terms of system theory (Figure 5.2). Variables that influence the process are called **inputs**. Some of these can be manipulated, so these are called **manipulated variables**. Typical manipulated variables are aeration intensity, waste flow rate, recycle flow rate and influent flow distribution. Other inputs are not manipulated or cannot be manipulated; these are defined as **disturbances**.

Some of the disturbances can be measured. Many, but not all, the disturbances to a treatment plant are related to the influent, such as the influent flow rate and concentrations. Other disturbances are caused by the operation of other processes than the activated sludge process, such as filter back washing or digester supernatant recycling. Disturbances may also be due to equipment failures. How a variable is labelled depends on the context and the corresponding system definition. For example, the waste flow rate can sometimes be manipulated. If not, it is considered a disturbance, for example when the waste flow rate changes owing to pump failure or blockage.

Variables that one is interested in and that are influenced by the inputs are called **outputs**. For example, the output respiration rate is influenced by the input (as a disturbance or as a manipulated variable) waste flow. However, in a different system definition, the same variable respiration rate can be considered as an input (disturbance), whereas another variable such as DO concentration acts as an output. Hence it is important to define the context of a process, in other words to identify the variables of interest (outputs) and the variables influencing them (inputs).

5.3 Controller structures

In addition to the three process system variable types (disturbance, manipulated variable and output) in a controller structure there is also a set point. In a controlled system (including process and controller) the set point and output always refer to one and the same variable: the **controlled variable**.

The standard **feedback** (FB) control scheme

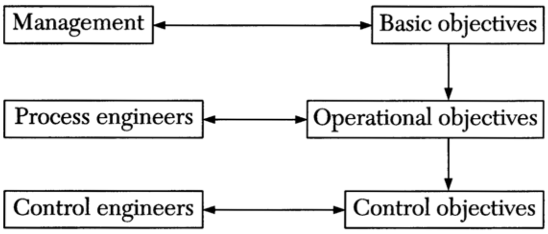


Figure 5.1. Levels of objectives and relation to professionals involved.

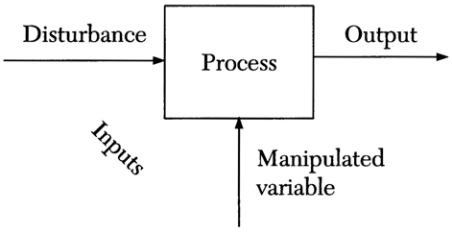


Figure 5.2. Activated sludge process system.

is depicted in Figure 5.3a. Measured variables are passed to the controller and compared with **set point** (or reference) values. The objective of the controller is to keep the measured value (of the controlled variable) as close as possible to the set point value, despite the disturbances (disturbance rejection). Usually the set point value is constant, but it can also be varying (set point tracking). As shown below, in **cascaded control** the output of one controller (the manipulated variable) becomes the set point of another controller.

When disturbances can be measured, **feedforward** (FF) control can be applied. The manipulated variable is adjusted to compensate for the anticipated effect of the disturbance on the controlled variable. The ideal is that the effects of the measured disturbance and the FF control action exactly cancel out, and there is no deviation from the set point. The basic design principle of an FF controller is illustrated in Figure 5.3b.

It is obvious that an FF controller needs a method to calculate how much adjustment of the manipulated variable is required to cancel out the effect of the disturbances, so a model is required. Because the result of the disturbance on the plant output has not yet been seen, the controller has to be able to calculate its consequence before it actually happens. A car driver, for example, acts with FF control. Any disturbance ahead, such as an uphill road or an obstacle, should be acted on before it has influenced the car behaviour (measured by speed and position). The driver needs a good (mental) model of the car's dynamics to compensate for such disturbances: for instance, he speeds up before he reaches the hill or turns at a sufficient distance from the obstacle. It is not possible to completely cancel the influence of a disturbance with FF control, because models and measurements are not perfect. It is therefore always strongly recommended to combine an FF controller with an FB controller (Figure 5.3c). The FF controller makes a fast compensation for the disturbance, whereas the FB controller adjusts on a slower time scale, acting on the measured response on the non-compensated part of the disturbance. This is how response speed can be combined with accuracy.

5.4 Examples

To illustrate the concepts of system descriptions and its relations to controller structures, let us consider two control strategies, DO control and respiration rate control. Before we look into the control configurations we have to understand the various cause–effect relations (models!). Figure 5.4 depicts three variables, substrate concentration S_S (here we consider only one substrate), DO concentration S_O and respiration rate r_O. It is apparent that r_O will be influenced by inputs such as pH, temperature, biomass concentration and toxicity. If the inputs are not manipulated or cannot be manipulated, they are considered disturbances. The influent substrate concentration $S_{S,\,in}$ will affect the substrate concentration S_S in the aeration tank, which in turn will influence r_O. Similarly, the aeration intensity F_{in} will affect S_O, which in turn will affect r_O. However, the coupling between r_O, substrate concentration and DO

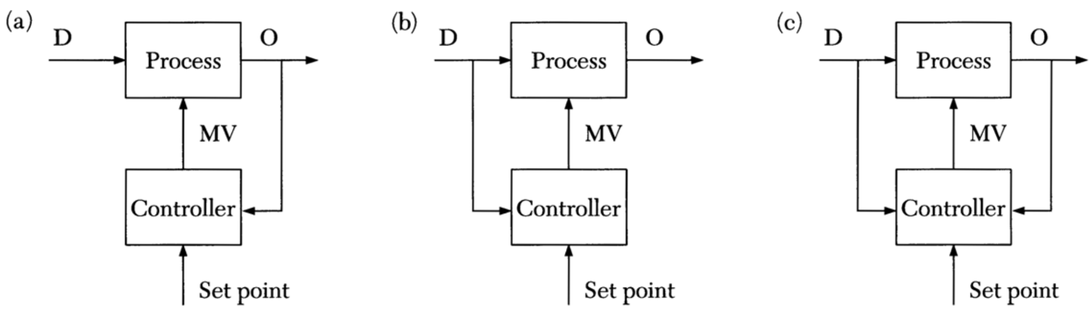


Figure 5.3. Controller structures: (a) feedback; (b) feedforward; (c) feedforward/feedback. D, disturbance; MV, manipulated variable; O, output.

concentration is bi-directional. A changing respiration rate will in turn influence the substrate concentration and the DO concentration. The actual direction of the cause–effect relationship depends on the control system definition specified by the control engineer with a particular control objective in mind.

Example 1: DO control strategy

Consider a traditional DO controller (Figure 5.5). The feedback part of the control is obtained by measuring the DO concentration (output variable). This value is compared with the DO set point, and the aeration intensity is subsequently manipulated to keep the DO concentration close to the set point despite disturbances. The feedback DO controller does not consider the respiration rate. *With respect to the process* the respiration rate r_O is a disturbance in the same way as any other disturbance. For example, assume that activated sludge is washed out from the clarifier or that a malfunction of the return sludge pump causes the biomass concentration to decline. As a result, r_O will drop. The feedback DO controller will notice that less air is needed to reach the DO set point value and decrease the aeration intensity, but it will not explicitly recognize the disturbance. A decreasing substrate concentration would have caused the same control action. If the respiration rate is measured in the aeration tank, this signal of the process disturbance can be fed forward to the controller, thus improving the control performance. This can be noted in the DO concentration because the transient deviation due to the disturbances in respiration rate will be significantly decreased. In the ideal case it will be cancelled out by the feedforward controller. The fact that there is a coupling back from the DO concentration to r_O, as shown in Figure 5.4, is not considered by this control structure.

Example 2: Cascaded DO control strategy

Usually the DO controller does not manipulate the aeration intensity directly via some valve or by changing the aerator power. Rather, the controller typically manipulates just the set point of the aeration intensity; that is, the aeration intensity desired to keep the DO concentration close to its set point. Then, a separate controller will manipulate a valve or aerator power so that the desired aeration intensity is accomplished (Figure 5.6). This is particularly valuable when, for instance, the valve is nonlinear, in other words it will have a different gain for different air flows. When one controller affects the set point of another controller it is a **cascaded** control system. The inner loop can be tuned completely independently of the outer loop. The DO controller is then easier to tune

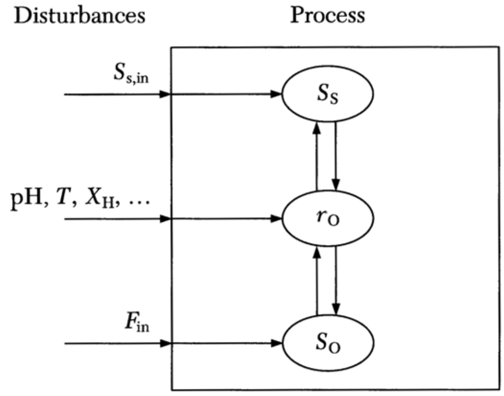


Figure 5.4. Relationship between substrate concentration S_S, DO concentration S_O and respiration rate r_O. Ovals indicate variables, and arrows cause–effect relationships.

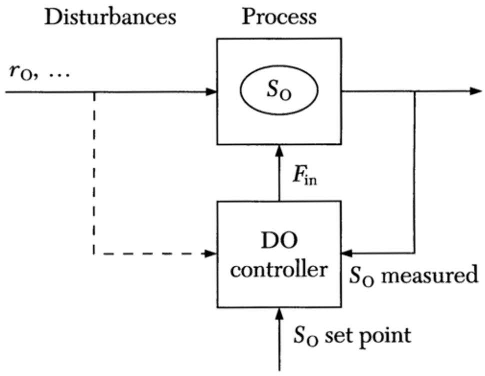


Figure 5.5. Traditional DO feedback control with potential feedforward from substrate concentration or respiration rate.

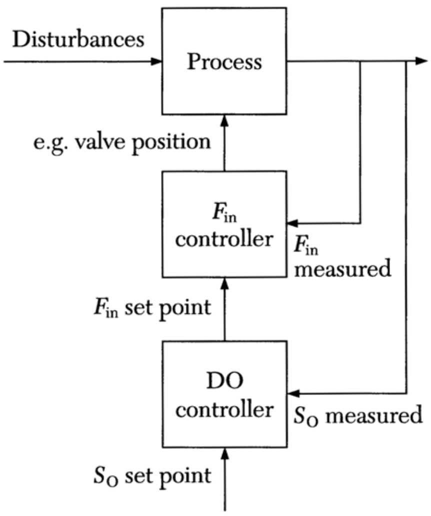


Figure 5.6. Cascaded control of DO.

and to commission. Note here that the 'aeration intensity controller' and 'DO controller' are different items.

Example 3: Respiration rate control strategy

As a comparison with example 1, consider a respiration rate control strategy (Figure 5.7).

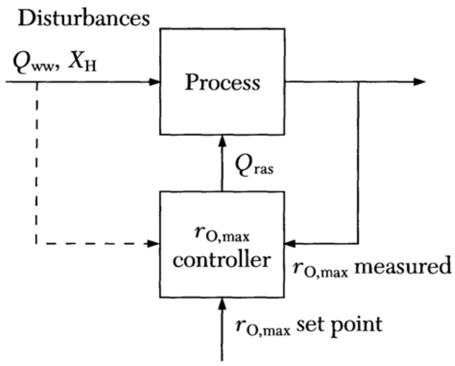


Figure 5.7. Respiration rate control, by manipulating return sludge flow (Q_{ras}), with possible feedforward from an influent flow measurement.

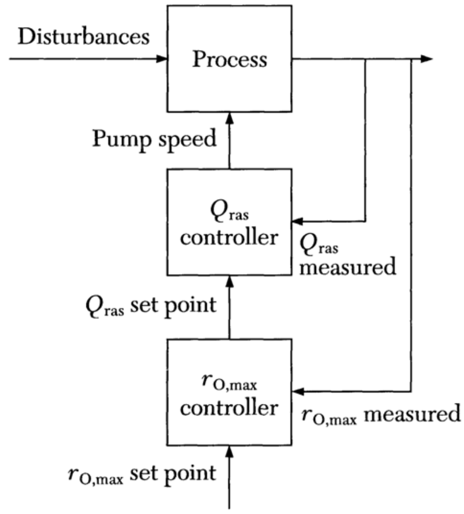


Figure 5.8. Cascaded respiration rate control.

The objective of the controller here is to keep the maximum respiration rate ($r_{O,\,max}$) close to its set point value. The maximum respiration rate is here used as a surrogate for the biomass concentration and the controller therefore aims at keeping the biomass concentration at a desired level, expressed as a $r_{O,\,max}$ set point. Consequently, the maximum respiration rate is measured and compared to the set point. The controller manipulates, for example, the return sludge flow Q_{ras} to achieve this goal. For the DO controller, r_O was considered a disturbance. Here r_O is the **controlled variable**. Note that the biomass concentration (X_H) can be considered an influencing variable of the maximum respiration rate that is changed by manipulating the return sludge flow rate so that $r_{O,\,max}$ is changed adequately. The controller does not specifically know the biomass concentration. The respiration rate is changed by disturbances, such as the influent flow rate pushing biomass out of the aeration tank into the settler. If the influent flow rate is measured, this signal can be fed forward to the controller. Ideally, the FF controller should command a change of the return sludge rate before the disturbance has appeared in $r_{O,\,max}$. Thus, a good model of the dynamics of respiration as a function of the influent flow rate is needed. Note that the choice of the controller structure imposes the directions of the cause–effect relationships between flow rate, respiration rate and activated sludge concentration.

Example 4: Cascaded respiration rate control

The scheme in Figure 5.7 can be further refined, as depicted in Figure 5.8. Instead of letting the maximum respiration rate controller influence the return sludge flow rate directly, it will change only the return sludge flow rate set point. Then an inner control loop, a Q_{ras} controller, will make Q_{ras} change until the return flow rate has reached the desired set point. The advantage of this cascaded control is that the outer loop, the respiration rate controller, does not have to deal with the dynamics of the recycle sludge pump: it is taken care of by the inner loop. Naturally, the cascaded control can be combined with an FF controller.

5.5 Concluding remarks

In this chapter some elementary control concepts were reviewed, to facilitate the discussion on respirometry-based control in the next chapter. It was shown that the objectives in wastewater treatment can be classified into three levels: basic objectives, operational objectives and control objectives, and that each of these is dealt with by a different group of professionals. The wastewater treatment process can be described by defining three kinds of process system variable: disturbances and manipulated variables (both considered as inputs) and outputs. On the basis of these variables, three basic controller structures were discussed: FB, FF and a combination of these. A number of examples were given and it was illustrated that respiration rate can be considered as a (measure of a) disturbance as well as a (measure of a) controlled variable in different system descriptions and control structures.

6. Respirometry in control of the activated sludge process

The original aim of the study reported in this chapter was to summarize the potential applications of respirometry, to evaluate the relative merits of the control strategies by using consistent criteria, and from that to develop a 'how-to-do' protocol. For reasons given below, however, the work had to be restricted to the presentation of a structured overview of strategies found.

This section addresses four items. First, the method by which different strategies were collected and the procedure adopted to decide on inclusion or exclusion of a strategy is presented. Secondly, the reasons are given for the absence of an evaluation of the strategies by the Task Group. Thirdly, the different possibilities for structuring the control strategies are reviewed, illustrating the great number of aspects of respirometry-based control strategies. Finally, the control strategies retained are described within the structure adopted and are illustrated with some examples.

6.1 Collection and delineation

A literature study and discussions with practitioners were done. Sixty years of literature were covered, as the first reference found dated back to 1936 (L.H. Kessler, 'Odeeometer: its place in the control of activated sludge plants', *Water Works and Sewerage* **83**, 13). Control strategies were retained in which information obtained from a respirometer was used in some way within the control strategy. Basically, all strategies are included in which the respiration rate or a deduced variable is used as input to the controller.

During the collection of these proposals and applications, no a priori judgement was made on the plausibility of the strategy. The measurement and control strategy and its implementation were assumed to be as the author intended them to be. As applications we considered bench, pilot and full-scale implementations of these strategies. A prerequisite for inclusion in the list of control strategies was that at least the controlled variable (that is, the control objective of the strategy) and the manipulated variable were clearly stated.

6.2 Why no evaluation of control strategies by the Task Group?

One of the goals of the Task Group was to evaluate control strategies in which respirometry plays a role. However, for three main reasons, given below, this task could not be completed.

6.2.1 Lack of insight and common terminology

One reason causing difficulties when evaluating the proposals is insufficient insight demonstrated in many papers and lacking overview by the proposers of one of the disciplines involved, namely control engineering and (bio)process engineering (Figure 5.1). Some problems encountered in control engineering proposals are due to a misunderstanding of measurements. Examples are the application of respiration measurements under wrong conditions or the belief that any respiration rate measurement principle provides a correct measurement of the respiration rate in the reactor. In contrast, process engineers tend to apply control theory intuitively. For instance, they do not provide a stability analysis of their proposal or have not considered tuning the controller's parameters adequately.

A related problem is a lack of common terminology. For instance the word 'control' is used in such combinations as 'waste flow control', 'MLSS control' and 'sludge age control', although 'control' has different meanings in each case. (In fact these aspects all pertain to one strategy: control of MLSS concentration by using waste flow rate as the manipulated variable with the secondary objective of tracking a given sludge age.) As a result, the Task Group had to devote significant effort to redefining the proposals to fit within the adopted control terminology (Chapter 5). In some cases the original objective could not be retrieved from the publications and there was a hazard that the Task Group would misinterpret the strategy.

6.2.2 Lack of consistent criteria for comparison

Another difficulty with the evaluation of the control strategies was that it is virtually impossible to compare the merits of different proposals when they are developed for completely different plant configurations, influent characteristics, process operations, etc.

Evidently, some restricted evaluations can be done directly on the proposal itself. On the one hand, an evaluation can be made in absolute terms. For instance, the stability of the proposed control strategy can be evaluated, or the appropriateness of an underlying assumption can be checked. On the other hand, a relative evaluation can be done. This is especially feasible for those proposals that have been evaluated within the reported study. Mostly this is done by comparing a performance criterion before and after the control strategy was implemented. For some studies, two or more strategies were tested on the same configuration and these results could have been reported in this chapter. However, it was felt that this would not have contributed to a good general evaluation of the usefulness and limitations of respirometry-based control. In fact, questions that one would like to answer on the basis of such evaluation (such as "Where would my plant performance benefit most if I were to acquire a respirometer: return activated sludge flow rate manipulation or influent flow distribution?") cannot be answered with the information currently available.

6.2.3 No evaluation by the proposer

A control strategy should preferably be evaluated by full-scale trials or, if this is not possible, by bench-scale tests. An alternative to practical tests is evaluation by computer simulations. In most proposals, however, no attempt was made to evaluate the performance of the suggested or implemented control strategy. It was not the mission of the Task Group to conduct detailed evaluations of the proposed control strategies. It is important, however, to realize why such evaluations were not conducted in these previous studies as this might be the cause for the slow introduction of respirometry-based control strategies. Three reasons can be given here.

First, few strategies are proposed with a preliminary simulation study because at the time that most of the strategies reported here were proposed, neither the simulation tools nor the generally accepted models in use today were available.

Secondly, in contrast with other sensors such as dissolved oxygen probes for which even microprobes are routinely built, not all respirometers can be down-scaled at will. Typical volumes of bioreactors contained within respirometers are up to 10 litres. Consequently, considerable (mixed liquor; wastewater) sample volumes are necessary for operating such respirometers. This has seriously hampered the use of these devices in bench-scale or even small pilot-scale tests (on which most of the development in control engineering is based). Indeed, the necessary sample volumes are too large not to create considerable disturbances to the facility by installing a respirometer.

Thirdly, because no cost–benefit could be associated with respirometry-based control, full-scale experimentation with respirometers and newly developed control strategies has not been encouraged. Worse, as in this way no cost–benefit results could be gathered, a vicious circle emerged. Today, models, simulation tools and computing power are up to the task of realistically evaluating respirometry-based control strategies a priori, and these studies could make it possible to break the vicious circle.

6.3 Classification of respirometry-based control strategies

Given the great number of respirometry-based control strategies, a listing as such is not informative. An attempt was therefore made to classify the control strategies according to some criterion that is easy to trace and therefore also useful for future classification. The following characteristics on which a classification could be based were considered: the location of the respirometer, the respirometric variable or deduced variable thereof, the control objective or controlled variable and, finally, the manipulated variable in the control strategy. Below, the possible values that these attributes were given are reviewed. The Task Group considered it important to list these as this might give the reader some perspective on the ubiquitousness of trials conducted with respirometry in control of activated sludge processes.

6.3.1 Location of respirometer

Respirometry-based control strategies have been proposed in which the respirometer has been located at nearly any spot within the wastewater treatment plant. Note that in this report the location of the measurement is not considered decisive for the interpretation of the measuring result (Chapter 4.1). If, for example, activated sludge from the aeration tank and wastewater from the influent line are combined in order to obtain respirograms (measured rate r_O[at, ww, resp]), the instrument can be located either at the aeration tank or at the influent line. In either case sludge or wastewater would be transported to the instrument. In an alternative measurement set-up, but with the same objective, the biomass is grown separately (measured rate r_O[scul, ww, resp]. Logically, the respirometer would then be located at the influent line, close to the plant or further upstream. Table 6.1 summarizes the possible origins of biomass and substrate.

6.3.2 Measured or deduced variable

The diversity of data that can be obtained from respirometers has obviously led to a considerable potential of using this information for the control of wastewater treatment processes. Apart from use of the respiration rate directly, the result of the measurement is frequently converted to a deduced variable (Section 4.3). All these, listed in Table 6.2, have been used in control strategies.

6.3.3 Controlled variable

A rather complicated issue encountered when analysing many proposals was to discover the actual controlled variable in the control strategy (see discussion in Section 6.2.1). In the end, the list presented in Table 6.2 was put together.

Notice that in this overview only the control objectives of the strategies are retained and not the operational or basic objectives (Figure 5.1). It is obvious that the basic objective of the strategy is to obtain good effluent at the lowest possible cost.

6.3.4 Manipulated variable

The variables that have been manipulated on the basis of respirometry encompass most actuators available in current treatment plants. The variables manipulated in feedforward and feedback manner by using respirometric information are listed in Table 6.3. Other manipulated variables, such as chemical dosage rate, nitrate recycle flow rate and sludge treatment return liquor flow rate, also have been reported. However, those publications do not meet the criteria for inclusion in this report.

Table 6.1. Instances of the origin of biomass and substrate (see also Figure 4.1)

Attribute	Origin of biomass and substrate
ww	Influent line of WWTP
at	Activated sludge tank (any location)
ras	Return activated sludge line
rl	Return liquor
scul	Specific culture, e.g. in an isolated reactor
at1	Inlet of plug flow reactor
at*n*	Outlet of plug flow reactor
eff	Effluent line of WWTP

6.3.5 Choice of manipulated variable as classification criterion

Classification of the strategies could be based on any of the different elements of a respirometry-based control system presented above, especially measured or deduced (input or output) variable, manipulated variable or controlled

Table 6.2. Measured or deduced variable, and controlled variable

Variable	Description	Measured or deduced	Controlled
B_I	Inhibitor loading rate		✓
B_V	Volumetric loading rate		✓
B_X	Sludge loading rate		✓
BOD_{st}	Short-term BOD	✓	✓
I	Inhibition (%)	✓	✓
I_A	I of autotrophs (%)	✓	
I_H	I of heterotrophs (%)	✓	
K_{NH}	Autotrophic saturation coefficient for S_{NH}	✓	
R_{COD}	Specific carbonaceous respiration rate	✓	✓
$r_{O,act}$	Actual respiration rate	✓	✓
$r_{O,end}$	Endogenous respiration rate	✓	✓
$r_{NH,max}$	Maximum nitrification rate	✓	✓
S_A	Concentration of VFA's	✓	✓
S_{NH}	Concentration of NH_4^+	✓	✓
S_{NO_2}	NO_2^- concentration		✓
S_{NO}	$NO_2^- + NO_3^-$ concentration		✓
S_O	DO concentration		✓
S_S	Concentration of readily biodegradable substrate	✓	✓
SBH	Sludge blanket height		✓
t.t.e.	Time to endogenous	✓	✓
X	Total solids	✓	✓
μ_{mA}	Maximum specific growth rate autotrophic biomass	✓	
θ_X	Sludge age		✓

Table 6.3. Manipulated variables

Symbol	Manipulated variable
K_La	Oxygen mass transfer coefficient
Q_{ras}	Flow rate of return activated sludge
Q_{was}	Flow rate of waste sludge
Q_{ww}	Flow rate of influent
f_{Qww}	Influent flow distribution
T_{cycle}	Cycle length in periodic process
Q_{store}	Flow rate of sludge storage

Table 6.4. Number of control strategies per class of manipulated variable and control scheme

Variable	FF	FB	FF/FB	Total
K_La	5	6	10	21
Q_{ras}	5	10	3	18
Q_{was}	5	6	2	13
Q_{ww}	7	6	0	13
f_{Qww}	4	4	0	8
T_{cycle}	1	2	0	3
Q_{store}	1	0	0	1
Total	28	34	15	77

variable. Discussions of the Task Group with interested parties revealed that some classifications are more prone to confusion and misunderstanding than others and it was decided, and approved at the IAWQ Specialised Conference on Sensors in 1995, that a classification based on the manipulated variable is the most appropriate because this variable is probably the easiest to identify in a control strategy.

6.4 Description of respirometry-based control strategies

About 80 control strategies in which respirometric data have a role were retained in the study. Table 6.4 summarizes and classifies these strategies according to the manipulated variable and the control scheme, namely feedforward, feedback or combined.

Note that, if respiration rates and deduced variables are used in a feedback manner, this implies that a respirometric control objective is being pursued. For instance, a control strategy that manipulates the mass transfer coefficient K_La in a feedback mode might aim to keep the respiration rate at a certain desired value. In an FF controller, the respirometric information is used to quantify a disturbance whose effect is to be anticipated by the controller. Finally, for a combined FF/FB controller the respirometric information can be used both to assess deviations from the set point (feedback) and to measure a disturbance (feedforward).

The number of strategies per class given in Table 6.4 is indicative of the efforts spent on their development. In fact, these numbers also reflect the importance inferred by the developers to the different manipulated variables and the type of control strategy (FF, FB, FF/FB). This importance is related to the expected economic benefit and the assumed reliability of these controller characteristics.

It is not the objective to present and explain all proposals for respirometry-based control strategies in this report. Rather, the main ideas will be illustrated and the reader is referred to the literature to find out more about these. For each of the manipulated variables, one or more examples (covering the different control schemes) will be presented in the next sections.

6.4.1 Mass transfer coefficient K_La

From Table 6.4 it is obvious that improving process behaviour by manipulation of the mass transfer coefficient has, as in general in activated sludge process control, also received most attention within the context of respirometry-based control.

Example 1 (FF)

Many authors have tried to do respirometric analysis with an influent sample (r_O[*, ww, *]) to predict the forthcoming oxygen demand in the facility and to calculate the setting of the aeration intensity. In a simpler approach, the respiration rate in the aeration tank is measured instead of being predicted from respirometry with an influent sample. As an example, for a given K_La–airflow relationship,

$$K_LA = \alpha F_{in} + \beta, \tag{6.1}$$

the necessary air flow rate F_{in} can be calculated from the oxygen mass balance over the aeration tank (with the inlet oxygen concentration assumed to be negligible):

$$\frac{dS_O}{dt} = K_La(S_O^* - S_O) - \frac{Q_{ww} + Q_{ras}}{V} S_O - r_O, \tag{6.2}$$

for a steady-state desired oxygen S_O value,

$$F_{in} = \frac{1}{\alpha}\left\{\frac{[(Q_{ww} + Q_{ras})/V]\, S_O^{setp} + r_O}{S_O^* - S_O^{setp}} - \beta\right\}. \tag{6.3}$$

As with all FF controls, the performance of such a strategy depends greatly on the quality of the underlying model that predicts the effect of the disturbance. In this case the performance depends on an accurate description of the K_La–F_{in} relationship (α, β), the appropriate values of the saturation concentration (S_O^*) the volume (V) and flow rates (Q_{ww}, Q_{ras}) and, if the respiration rate (r_O) in the aeration tank is to be calculated from an influent measurement, the model that predicts r_O. Finally, it must be stressed that even then the desired value will be reached only under steady-state conditions.

Example 2 (FB)
Strategies have been proposed that aim at maintaining the respiration rate at a particular value (FB control) by manipulating the aeration intensity, thus making the degradation process oxygen limited. It is obvious that in this way substrate degradation will be incomplete, which might be desirable in certain circumstances, for example when the controlled activated sludge system is part of a two-sludge system in which the second system is a denitrifying one. It is clear that the air supply and the concomitant energy costs are reduced by this strategy.

Example 3 (FF/FB)
Probably one of the most studied applications of respiration rate measurements is its addition as a feedforward component to the standard feedback dissolved oxygen control. In this way controller performance is increased further as the effect of changing respiration rates (which are disturbances of the dissolved oxygen concentration; Figure 5.4) can be anticipated. Respiration rate measurements have also been used as input to a gain scheduling scheme that ensures optimal performance of a standard dissolved oxygen controller under the time-varying conditions to which the activated sludge process is subject.

One of the 'classics' in advanced wastewater treatment process control is a combined estimation/adaptive control algorithm developed in the early 1980s. The basic idea is to loosen the strict control that can be obtained with a standard feedback dissolved oxygen controller and with the induced dynamics in the dissolved oxygen concentration to estimate (i) the respiration rate and (ii) the time-varying relation between the mass transfer coefficient K_La and the applied control input. This high-quality information then allows adjustment of the controller to maintain good performance under changing load conditions or equipment performance.

Example 4 (FB)
Measuring the respiration rate of biomass from the outlet of the aeration tank (r_O[atn, –, inst]) has been used as input to the outer loop of a cascade controller. The latter calculates the dissolved oxygen set points in the previous stages of a plug flow-like aeration tank, which may make the process oxygen-limited. In this way substrate can be distributed over the next compartments. This cascade control system ensures that the oxygen demand is evenly distributed over the different stages.

Example 5 (FB)
A MIMO (multiple input, multiple output) strategy has been suggested in which the aeration intensity and the return activated sludge flow rate are manipulated on the basis of a dissolved oxygen measurement in the aeration tank and a measurement of respiration rate with a sample from the effluent line, indicating effluent pollutant load (r_O[*, eff, *]). The study was valuable as it also involved adaptation of the control law using only these two measurements .

6.4.2 Return activated sludge flow rate Q_{ras}

The return activated sludge flow rate is mostly, if changed at all, manipulated on the basis of either influent flow rate measurements (ratio control) or (turbidimetric) biomass concentration measurements. The main idea behind these control strategies is to maintain a desired sludge loading rate B_X. The control strategies manipulating Q_{ras} on the basis of respirometry have the same idea.

Example 1 (FF)
Feedforward control strategies have been proposed in which measurements of respiration rates with two different biomass sources are combined to predict the loading rate. In one case the respiration rate of the return mixed liquor (r_O[ras, –, inst]) is measured as an indication of the biomass concentration in the return line, and this information is combined with a measurement of the respiration rate in the first part of a plug flow-like biological stage r_O[at1, –, inst] to calculate the necessary return sludge flow rate for a given sludge loading rate. This strategy was later extended with a feedback component to eliminate the errors induced by the modelling errors that are always present when only FF control is applied. The control objective of this combined strategy was to keep the respiration rate at the outlet of the aeration tank (r_O[atn, –, inst]) at a desired low value, indicative of low remaining substrate concentrations. Summarizing, in this strategy respirometric values of three different biomass sources are combined to manipulate a single variable, the return activated sludge flow rate.

Example 2 (FB)
Feedback control systems have been developed with the objective of maintaining a certain respiration rate, indicative of the biomass concentration in the aeration tank. A number of exercises have been performed in which the specific oxygen uptake rate R_O is controlled, whereas in another approach an active biomass concentration is deduced from the measured respiration rate and compared with the desired active biomass concentration.

Example 3 (FB)
Another FB control strategy uses the ratio between the respiration rate of sludge from the outlet of the aeration tank (r_O[atn, –, inst]) and the maximum respiration rate of the same sludge sample in the presence of an excess amount of

wastewater (r_O[atn, ww, inst, exc]). By manipulation of Q_{ras} the control objective is to keep this ratio at a predefined level. It is assumed that the ratio is indicative of the extent of substrate removal at the outlet of the aeration tank, i.e. the lower the ratio the better.

Example 4 (FB)
The MIMO controller of example 5 above (section 6.4.1) is, in addition to being used to manipulate the aeration intensity, also used to manipulate Q_{ras} to control effluent substrate concentrations as measured with a respirometer.

Example 5 (FF/FB)
In another MIMO controller, respirograms obtained under different experimental conditions are used to characterize the wastewater and the activated sludge (r_O[at, *, resp]). This information is used subsequently in a control strategy as a measure of the disturbance, and to adjust the parameters of the model-based control algorithm. Supplemented with additional (turbidimetric) biomass concentration measurements, the aim of the control strategy is to maintain a constant biomass concentration in the aeration tanks and keep the sludge blanket height constant by manipulating the return and waste sludge flow rates.

6.4.3 Sludge waste flow rate Q_{was}

Sludge wastage control is traditionally performed manually by daily measurements of biomass concentrations. Adjustment of the waste flow rate is never drastic. Given the slow dynamics of the sludge concentration, this smooth manipulation is quite acceptable. The main objective of the control actions is to maintain a certain solids retention time (sludge age) or a desired biomass activity in the system. Some strategies will be reviewed below that attempt to manipulate the sludge wastage by using respirometric biomass activity measurements.

Example 1 (FF/FB)
As explained in the previous Q_{ras} example, a MIMO control strategy with respirometric information obtained with influent has been used to manipulate both Q_{ras} and Q_{was} with the aim OF maintaining the sludge concentration and the sludge blanket height at a desired value. A rather slow controller has to be implemented to guarantee stability.

Example 2 (FF)
Similarly to the Q_{ras} control strategy presented in example 1 above, it has been proposed to manipulate Q_{was} in an FF control scheme on the basis of a combination of (i) the respiration rate of the return activated sludge (r_O[ras, –, inst]) and (ii) the respiration rate of the sludge from the inlet of a plug flow-like aeration tank (r_O[at1, –, inst]). With this information sludge is wasted to such an extent that the sludge loading rate B_X is kept at a desired value. Here, too, a slow (low-gain) controller is required to prevent excessive oscillations in biomass loading rates.

Example 3 (FB)
An FB control strategy has been proposed that uses the ratio between the respiration rate from the outlet of the aeration tank (r_O[atn, –, inst]) and the respiration rate of the same mixed liquor sample to which an excess of wastewater is added (r_O[atn, ww, inst, exc]). This ratio is an indication of the extent of substrate removal. The higher this ratio is, the more the sludge is overloaded indicating that the sludge concentration is too low to deal with the waste load. The control strategy therefore consists of manipulating Q_{was} to maintain a certain ratio. Because a diurnal variation of this ratio will be observed, appropriate averaging of the measured ratio is needed before it is submitted to the controller.

Example 4 (FB)
A simpler control strategy for Q_{was} uses a measurement of the respiration rate of the mixed liquor leaving the aeration tank early in the morning. At this time of the day, the sludge is assumed to be in an endogenous state so that the measured respiration rate would be a measure of the active biomass concentration. Hence, sludge wasting on the basis of this measurement allows maintenance of the sludge activity at a desired level. Evidently, the basic concept of an endogenous respiration rate can also be implemented in a different way, for example by incorporating a holding tank in which the sampled mixed liquor is brought to endogenous state before the respiration rate is measured (r_O[at, –, intv]).

6.4.4 Influent flow rate Q_{ww}

Although the wastewater flow cannot really be manipulated at will, some possibilities may exist when rain detention basins are available or when the capacity of the sewer system can be taken advantage of. Especially in industrial plants, calamity basins are constructed for emergencies. Basically the purpose of manipulating the influent flow rate is to protect activated sludge processes against toxic spills or to balance the load.

Example 1 (FF)
One of the most widespread examples of FF control is its application in protection of a treatment process against toxic spills. Respirometry can quickly detect the presence of toxic substances in an influent, and this information can be fed forward to a control system that can manipulate the intake of such wastewater to a level at which no detrimental effects on plant performance are predicted. Provided that the capacity to store this toxic wastewater temporarily is available, this strategy is the most appropriate to deal with toxic wastewaters, as all the wastewater will eventually be treated.

Example 2 (FF)
Load balancing has been advocated by many authors. Respirometric measurements involving additions of wastewater samples (r_O[*, ww, *]) can provide insight to the pollutant load and, provided that an appropriate model is used, allow calculation of the flow rate that gives a desired waste loading to the plant. Because it is a feedforward scheme, no information on the result of such control strategy is fed back to the controller so that any (modelling or measurement) errors will degrade the performance of the control strategy.

Example 3 (FB)
Several attempts have been made to measure respiration rate of the mixed liquor as an indication of the pollution load. This information is subsequently used in feedback mode to adjust the intake of wastewater to keep the respiration rate constant at a desired value. In this way it is attempted to obtain a desired loading of the sludge. In most cases the respirometer samples at the head of the aeration tank to allow sufficiently fast reaction to increased loadings. Sampling at the end of the aeration tank can lead to a delay between a load change and a measurement of its effect. This would hamper the effectiveness of a control strategy that used such delayed information.

6.4.5 Influent flow distribution f_{Qww}

In a number of plants the possibility exists to distribute the influent flow over different inlets along a plug flow-like aeration tank. This mode of operation is termed **step feeding**, and manipulation is mostly based on influent flow rate measurements as it is mostly used to deal with hydraulic overloads. Bypassing wastewater to the receiving body can also be considered a form of influent flow distribution and is sometimes used in case the hydraulic capacity of the plant is exceeded.

Example 1 (FF)
Control actions have been proposed in which toxic wastewaters are allowed, as a last resort, to bypass the treatment plant in the hope that the dilution effect of the receiving body is sufficient to attenuate the damage of the toxic substance. This strategy protects the treatment facility from considerable damage that might take it out of action for some time, with possibly more damage to the environment than bypassing the toxic pulse.

Example 2 (FF and FB)
In two-stage systems the idea has been formulated and implemented to balance the load over the two sludges with a respirometric measurement between both stages. Basically, an FB control on the first stage and an FF control on the second stage are used in this set-up. The objective of the control strategy is, for instance, to optimize nitrogen removal in the second stage by releasing more or less carbonaceous material to it.

Example 3 (FB)
The specific oxygen uptake rate R_O has been a deduced variable often applied as input to a step feed control system. The driving force for the development of such control strategies was the intent to balance the load over different aeration tanks positioned in series. Keeping R_O at a specified value above the typical endogenous respiration rate ensures that some of the pollutants still have to be degraded at the location where the respirometer is sampling mixed liquor. In some strategies a respirometer samples from the outlet of the aeration tank. In another proposal R_O is measured along the aeration tank and an objective of the controller is specified that consists of maintaining the mean value of all measured R_O on a specified value and to keep the variation in R_O to a minimum. All this is performed by manipulating the distribution of wastewater f_{Qww} along the aeration tank.

Example 4 (FF)
Finally, a feedforward strategy was suggested in which the overall respiration rate in the aeration tanks is used to deduce the load to the plant. With this information, influent flow distribution is manipulated in such a way that the aeration capacity is used in an (energy) optimal way. At low loading all wastewater is directed to the last tank, and sludge can be stored in the first tanks for use during more highly loaded periods when the feed is introduced increasingly towards the head of the facility.

6.4.6 Cycle time T_{cycle}

Cycle time is an important variable in periodic processes for biological nutrient removal because an optimal scheduling of redox conditions (aerobic, anoxic, anaerobic) must be achieved. Classic systems for nutrient removal that are based on this time scheduling are alternating systems and sequencing batch reactors (SBR).

Example 1 (FB)
The activity of the two nitrification steps (oxidation of ammonia to nitrite in the first step and oxidation of nitrite to nitrate in the second) can be obtained at regular intervals from a specific respirometric experiment (r_O[at, –, resp, inhibitor]). This information has been suggested as input to a controller that switches off aeration as soon as the rate of the first reaction step (ammonia oxidation) drops significantly. This drop indicates exhaustion of the ammonia from the mixed liquor. Such a control strategy was shown to reduce aeration costs, and it provides a means of increasing the cycle time for the subsequent denitrification period.

Table 6.5. Occurrences of proposals (p) and applications (a) of respirometry-based control strategies

	FF		FB		FF/FB		Total	
Variable	p	a	p	a	p	a	p	a
K_La	2	3	3	3	6	4	11	10
Q_{ras}	5	0	9	1	3	0	17	1
Q_{was}	5	0	5	1	2	0	12	1
Q_{ww}	4	3	4	2	0	0	8	5
f_{Qww}	1	3	2	2	0	0	3	5
T_{cycle}	1	0	1	1	0	0	2	1
Q_{store}	1	0	0	0	0	0	1	0
Total	19	9	24	10	11	4	54	23

Example 2 (FF)

For a plug flow-like reactor it has been suggested to use a respirogram obtained from batch experiments with a well-defined mixture of wastewater and sludge to manipulate in feedforward manner the required aerobic volume for complete nitrification (r_O[at, ww, resp, S_{t0}/X_{t0}]). This control strategy could also be classified among the controllers manipulating K_La, but clear similarity between plug flow and SBRs allows its inclusion here. Indeed, the aerobic volume fraction in a plug flow-like reactor corresponds to the cycle time in the time schedule of a SBR.

Example 3 (FF)

Respirometry has recently been suggested as a basis for control of biological phosphorus removal systems. The respirometric information is used to adjust the cycle time of the anaerobic phase. The principle is that the respiration rate in a reaerated mixed liquor sample taken from the anaerobic reactor (r_O[at, –, resp]) will generate high respiration rates when readily biodegradable substrate is still present, whereas the anaerobic phase can be interrupted when the carbon source is no longer present as indicated by a decreased respiration rate.

A similar control strategy has been proposed for interrupting the denitrification phase. Here the measurement set-up is similar, i.e. a mixed liquor sample is taken from the anoxic reactor and, after reaeration, respiration rates are indicative of the presence of readily biodegradable substrate. When nitrate is no longer present in the mixed liquor sample, readily biodegradable substrate concentration will be higher, as indicated by an increased respiration rate. Hence, the respiration rate measured in the reaerated sample will be a good indication of the termination of denitrification and can be used as input to a control strategy with T_{cycle} manipulation.

6.4.7 Sludge storage flow rate Q_{store}

In some wastewater treatment plants provision is made to store sludge temporarily. This storage capacity can be used to deal with hydraulic disturbances that could lead to settler washout, but stored sludge can also be activated when increased biological activity is required to accommodate higher loads. Respirometric measurements can trigger the release of sludge from the sludge storage tank.

6.5 Concluding remarks

In Table 6.5 an overview is provided of the occurrences of the different control structures dealt with in this review. A differentiation has been made between control strategies that were only proposed in the paper and the ones that were also applied on a laboratory, pilot or full scale.

First, from the table it is obvious that a large fraction of the proposals were never applied. Secondly, one would expect that the feedforward proposals would have difficulty in working without a feedback component to correct for the residual error, and this should be reflected in a smaller fraction of the proposals actually being applied in practice. However, one finds similar ratios between proposals and applications for the three classes of control strategies (FF, FB and FF/FB). Thirdly, if one focuses on the total number of control actions proposed and applied, it is obvious that the manipulations of the aeration system on the basis of respiration rate data have been successfully applied, as have the strategies manipulating the wastewater inflow or its distribution. The last two have to do mainly with the toxicity prevention that can be achieved by this manipulation, whereas the former is due to an economic incentive, namely aeration cost. Return and waste activated sludge flow rates have attracted much attention and several proposals have been generated, but the application of these control strategies is clearly lagging behind. For the waste flow rate (a slow controller), it is probably due to the fact that control based on laboratory analysis is more than sufficient within the current state of treatment plant operation. For the lack of application of return activated sludge control strategies it is hypothesized that this manipulation might have too little control authority.

Finally, this overview has made clear that the creativity of using respirometry in control of activated sludge processes has been significant, but that the stage has been reached where unbiased evaluations are required that will support the user community in deciding on better respirometer set-up/control strategies. Future work will have to bring the necessary information together.

7. Summary and perspectives

This Scientific and Technical Report, prepared by the IAWQ Task Group on Respirometry, has covered different aspects of respirometry-based control for activated sludge processes. We have devoted considerable effort to providing clear definitions and introductions of the different elements of relevance to respirometry-based control.

In the first chapter the fundamentals of respiration were elucidated from a biochemical, modelling and operational point of view. It was shown that (aerobic) respiration in a wastewater treatment control context has a somewhat wider meaning than the strict biochemical definition, in which it stands for oxygen consumption in the electron transport chain by heterotrophic organisms (including protozoa) and autotrophs such as nitrifiers. Oxygen utilization by a number of enzymic and chemical oxidation reactions may be part of the observed respiration rate. Some qualifications used in relation to respiration rate (endogenous, maximum, nitrification, etc.) were placed in their operational context. The relation between respiration rate measurements and the actual treatment processes (substrate removal and growth) was established, with special focus on the assumptions underlying this relation. It was indicated that basically three phases can be discerned in describing a system where respiration occurs: (1) biomass, (2) liquid phase and (3) gas phase.

The fact that measurement of respiration rate cannot be done in the biomass itself left two phases for measurement. This led to the main classification of the respirometric measuring principles: gas-phase and liquid-phase principles. The review of respirometers determined that specifying whether the phases are static or flowing allows the classification of all measuring principles found. Hence, in total only eight measuring principles exist. An analysis of the way in which these principles allow the determination of respiration rate data was performed by using oxygen mass balances on the gas and liquid phase. In each case indications were given on how these mass balances must be used and what assumptions have to be made. Some practical implementation aspects were mentioned, without aiming for an exhaustive description of existing respirometers. It was recognized that it can be difficult to consider a respirometer as a traditional sensor, as it contains a reactor in which different components or process streams are combined under specific measurement conditions.

Once the respiration rate measuring principles were established, attention was turned to the variables that can be obtained by using a respirometer. It was stressed that a respirometer is a sensor that is somewhat special in the sense that the values obtained have little meaning unless they are accompanied by additional information on the conditions under which they were obtained. The Task Group found that at least three attributes must be specified to interpret respiration rate measurements: (1) biomass source, (2) type of substrate added and (3) time aspect. As guidance, a nomenclature was proposed to communicate these attributes concisely. As respiration rate measurements can be performed with a considerable degree of freedom, the information content of the resulting data allows a great amount of high-quality information to be deduced, for example by combining respiration rate data with other measurements or a priori knowledge in the form of models. Deduced variables were defined as those variables that result from calculations performed with one or more measured respiration rate values. The calculations done on respiration rate could be classified into four groups: arithmetic, comparison, integration and parameter estimation.

Before the respirometry-based control strategies were reviewed, an introductory chapter on elementary control concepts was provided. From the literature study and the discussions with professionals it had become clear that a considerable gap exists between process and control engineers who work together to create and implement control strategies. Although control theory in itself was not an issue for this report, it was felt useful to review the basic control engineering concepts and, in this way, to state clearly what is meant in the terminology used in the overview of respirometry-based control strategies. Attention was focused on system description (different types of variable) and controller structures (feedforward, feedback and their combination). In addition, a simple but typical example of a respirometry-based control strategy was given to illustrate these concepts. The same example also illustrated how important it is to state clearly the control scheme of a proposal to prevent confusion or misinterpretation.

All the material presented up to this stage could be seen as fundamentals needed to interpret and implement the control strategies reported in the review. First, it was explained that not all proposals found in the literature and communicated from the field were retained for inclusion. Strict delineation was made between those that were retained and those that were not. Only those proposals that clearly stated a control objective and variables of the system description were included. Although the original intention of the Task Group was to evaluate the reported strategies, it was found that the information necessary for unbiased evaluation on the basis of consistent criteria was not available and that this information could not be generated within the frame of the existing Task Group. The mission of the Task Group was therefore redefined to provide a state-of-the-art description of the strategies in a first report, and to establish a new expanded Task Group that will evaluate the strategies and report by the year 2000 in a follow-up Scientific and Technical Report.

A clear classification system for control strategies is very useful. Possible candidate features with which the strategies can be classified are: location of measurement, measured or deduced variable, controlled variable and manipulated variable. Many controlled variables identified are related to many aspects of the treatment process, illustrating the vast potential for respirometry to control treatment processes.

It was decided that the manipulated variable was the best choice for classification because it leaves least risk for confusion. Subsequently, each of the proposed control strategies was classified according to the following manipulated variables (listed in order of number of strategies proposed):

- oxygen mass transfer coefficient
- flow rate of return activated sludge
- flow rate of waste sludge
- flow rate of influent
- influent flow distribution
- cycle length in periodic process
- flow rate of sludge storage.

Within these groups the strategies were ordered further according to their control scheme, namely feedforward, feedback or a combination. It can be concluded that a considerable number (35%) of strategies have been proposed in a feedforward scheme despite the potential danger of poor control performance if no feedback compensation is used. In total, only one-third of the proposals were applied. Most of these applications (85%) were controllers manipulating oxygen mass transfer coefficient, flow rate of influent, or influent flow distribution. The latter two dealt mainly with toxicity protection and load balancing. Many proposals were made on return and waste flow rates, but only 5% were finally tested on a full, pilot or bench scale.

It is hoped that this Scientific and Technical Report will help to encourage further developments of new respirometers. We believe that the clear definitions and the illustrations of potential reasons for confusion should improve communication. We hope to have inspired control engineers and process engineers in their development of strategies for better wastewater treatment operation, and we look forward to more extensive introduction of respirometry in practice.

We expect developments that lead to greater sensor reliability, for example by the inclusion of local intelligence that performs error detection, diagnosis and remediation. We observe developments in which the information content of variables deduced from respiration rate measurements is substantially increased and in which an increasingly wide spectrum of wastewater treatment aspects is covered. We expect to see novel control strategies developed by the many researchers and practitioners working with respirometry.

The future mission of the IAWQ Task Group on Respirometry has been well defined and work has already been initiated. The aim is to evaluate respirometry-based control strategies by using a simulation benchmark. The latter is a protocol in which a standard wastewater treatment plant is simulated under realistic influent conditions and with the control strategy implemented in the model. An objective function that encompasses treatment costs, effluent quality, etc., will be used to create a performance index. Results of this benchmark evaluation are expected to be presented by the year 2000 in the second Scientific and Technical Report from the Task Group on Respirometry.

Appendix: literature on respirometry

Literature related to respirometry has been arranged into six categories:

b background material on respirometry (biochemistry, monitoring, modelling and control)
m respirometric measuring principles (including implementation aspects)
c respirometry-based control strategies
k kinetics and modelling with respirometry
t respirometry-based toxicity detection
o other topics related to repirometry (biodegradability, etc.).

Evidently, papers can deal with more than one aspect and this should be reflected in this literature overview. Consequently, we have classified the papers according to their main theme and have added symbols (**b**, **m**, **c**, **k**, **t**, **o**) to indicate other themes covered in the mentioned paper.

As any literature review this reference list will be outdated by the time it is published, and some publications might be missing. However, we trust that the list in its current state will provide much background information related to respirometry. Nevertheless, we feel that it is worth while to update the list continuously. To this end, the list will be available on the IAWQ World Wide Web site (http://www.iawq.org.uk/) and new references will be added as they are found. We shall appreciate your help in improving the list, for example by sending us references related to respirometry.

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Appendix: manufacturers of respirometers

Company	Country	Address	Tel/fax	Brand name/principle (G or L)
Anatel Corporation	USA	2200 Central Avenue Boulder, CO 80301	t: 1 303 442 5533 f: 1 303 447 8365	
Anjou Recherche	France	109-111 rue des Cotes F-78600 Maisons-Laffitte	t: 33 34 93 34 67 f: 33 34 93 34 69	Biosurveyor
Arthur Technologies	USA	P.O. Box 1236 Fond du Lac WI 54936-1236	t: 1 920 922 6970 f: 1 920 922 1085	(G)
Bioscience Inc.	USA	1550 Valley Center Parkway Suite 140 Bethlehem, PA 18107	t: 610 974 9693 f: 610 691 2170	(G)
Challenge Environmental Systems, Inc.	USA	P.O. Box 3671 Fayetteville, AR 72702	t: 1 814 466 2232 f: 1 814 466 2234	AER-200, TOX-400 (G)
Columbus Instruments	USA	P.O. Box 44049 Columbus, OH 43204	t: 1 614 276 0861 t: 1 614 276 0529 f: 1 614 276 0529	Micro-Oxymax (G)
Cosa Instrument Corporation	USA	55 Oak Street Norwood, NJ 07648	t: 201 767 6600	BIOX-100 Continuous on-line BOD Monitor
Edmund Bühler G.m.b.H.	Germany	Rottenburgerstrasse 3 D-72411 Bodelshausen	t: 49 74 7170 70 f: 49 74 7170 7188	AAM (L)
Geotech Environmental Equipment, Inc.	USA	1441 W. 46th Ave. #17 Denver, CO 80211	t: 1 303 433 7101 f: 1 303 477 1230	
Gimat GmbH Umweltmesstechnik	Germany	Obermühlstrasse 70 D-82398 Polling	t: 49 881 6280 f: 49 881 62815	RESPIROFIX
Hach Chemical Co.	USA	Loveland, P.O. Box 389 CO 80539-0389	t: 1 970 669 3050 f: 1 970 669 2932	(G)
Kelma	Belgium	Antwerpsestraat 154 B-2845 Niel	t: 32 3 844 23 42 f: 32 3 888 5156	RODTOX (L) Nitrox (L)
LAR Analytik & Umwelt Messtechnik GmbH	Germany	Postfach 11 04 28 D-10834 Berlin Tempelhofer Ufer 23-24 D-10963 Berlin	t: 49 30 278 9580 f: 49 30 216 2004	BioMonitor (L)
Manotherm B.V.	The Netherlands	P.O. Box 5180 NL-3197 ZH Botlek Rotterdam	t: 31 10 416 9011 f: 31 10 416 9695	RA1000 (L)
Medingen GmbH	Germany	Lesskestrasse 1 D-01705 Freital		BOD Module
Minworth Systems Ltd	UK	Castle Vale Ind. Estate Maybrook Road Sutton Coldfield B76 9AL	t: 44 121 313 1709 f: 44 121 313 2180	(L)
N-con Systems Co., Inc.	USA	Clean Waters Bldg. PO Box 809, 180 North Street, Crawford, GA 30630	t: 800 932 6266 t: 706 743 8110 f: 706 743 8114	Comput-OX (G)
Neurtek Medio Ambiente	Spain	Araba, 45-Apdo. 200 20800 Zarautz (Guipuzcoa)	t: 43 13 1441 f: 43 13 0241	BM3 (L)

[*continued overleaf*]

[*continued*]

Company	Country	Address	Tel/fax	Brand name/principle (G or L)
ORION Research USA Inc.	USA	500 Cummings Center Beverly, MA 01915	t: 1 978 922 4400 f: 1 978 927 3932	ORION BOD_{fast} (G)
Phox Systems Inc.	USA	4400 S. Cedarbrook Road Allentown, PA 18103	t: 215 366 0171	
Professional Test Systems	UK	Summer Court, Manafon Welshpool, Powys SY21 8BJ		BOD-1 Biochemical Oxygen Demand Analyser
Stip Siepmann und Teutscher G.m.b.H.	Germany	Siemensstrasse 2 D-64823 Gross-Umstadt	f: 49 60 787 8688	BOD-M3, STIPTOX (L)
Voigt GmbH	Germany	Postfach 1940 D-7920 Gadenheim		Sapromat (G)
Wallas and Tiernan Pacific Pty. Ltd	Australia	P.O. Box 373, Artarmon NSW 2064	t: 6 12 9436 0375 f: 6 12 9438 4881	RACOD (L)
WTW	Germany		www.wtw.com	OxiTop BOD (G)

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Scientific and Technical Report No.7

Respirometry in Control of the Activated Sludge Process: Principles

This report is a synthesis and organization of the concepts and principles of respirometry in control of the aerobic wastewater treatment process. It is directed at an audience of researchers and practitioners dealing with the operation and control of aerobic treatment processes, and it can also be used as a primer on respirometry for graduate students.

The report describes the principles of measurement of respiration rate, the transformation of measurement data into other types of information, and the application of the obtained information in process control strategies. Some fundamental concepts on biological respiration and process control are provided to assist the reader with understanding the principles. A structured overview comprises some eighty control strategies in which respirometry plays a role. To enable the reader to consult the information sources, an extensive literature list of over 500 references is included and classified into six themes.

An evaluation of the respirometry-based control strategy and a how-to-do protocol for existing and new strategies will be published in a second report, which is envisaged for publication in AD2000.

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