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RESPIROMETRY IN CONTROL OF THE ACTIVATED SLUDGE PROCESS

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ABSTRACT

This paper summarises progress of the IAWQ Task Group developing the Scientific and Technical Report (STR) on respirometry in control of the activated sludge process. The significance of respirometry in activated sludge systems is explained from a biochemical background. A classification is proposed which includes all respirometric measuring principles described in the literature. The different respiration rates that can be measured are reviewed and some variables that can be deduced from respiration rate are discussed. Some elementary control concepts will be provided that are necessary for the evaluation of respirometry-based control strategies. Finally, a number of respirometry-based control strategies will be classified and discussed.

KEYWORDS

Activated sludge; control; oxygen uptake rate; respirometer; respirometry; Scientific and Technical Report; sensor

INTRODUCTION

Respirometry is the measurement and interpretation of the respiration rate of activated sludge. The respiration rate is the amount of oxygen per unit of volume and time that is consumed by the micro-organisms. For a long time respirometry has been recognized as a valuable basis for controlling the activated sludge process. The reason for this is that respiration rate is directly linked to two important biochemical processes that must be controlled in a wastewater treatment plant: biomass growth and substrate consumption.

There is a strong relationship between respiration rate and dissolved oxygen (DO) concentration in activated sludge. Because DO concentration can be measured relatively easily and reliably, it has been used frequently in control of the activated sludge process. However, the absolute value of DO concentration does not give sufficient information on the growth and substrate utilization *per se.* DO concentration-based control is not similar to respiration rate-based control!

Measurement of respiration rate has been the subject of many studies and a number of measuring techniques have been developed. Unfortunately, in the description of respirometers there is more confusion about operating principles than with any other instrument, the descriptions being characterized with terms like: continuous, semi-continuous, batch, in-line, on-line, in-situ, etc. The reason for this confusion is that the characterization can pertain to the operation of the respirometer, which often is a small activated sludge reactor by itself, or to the way it interacts with the treatment plant.

Many respirometry-based control strategies have been proposed in the literature but very few real implementations are reported. The small number of successful practical applications is partly due to inadequate measurement techniques and a lack of understanding of the information content of respirometric data. Furthermore, confusion arising from inconsistency in implementation methods and use of terminology has hampered the introduction of respirometry-based control.

Realising 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 this subject. The aim of the STR is to generate new insights by evaluating existing knowledge present in literature and practice and identify further needs. This paper summarizes the work done so far. The draft STR will be submitted to an international panel of reviewers consisting of practitioners and academics and their feedback will be used to prepare the final report.

In this paper the significance of respirometry will first be explained from a biochemical background. Next, a classification will be proposed which includes all respirometric measuring principles. The next section discusses the different respiration rates that can be measured and the variables that can be deduced from these. A section on elementary control concepts will provide the basics necessary for the evaluation of respirometry-based control strategies. Finally, respirometry-based control strategies will be classified and discussed.

SIGNIFICANCE OF RESPIROMETRY

The primary objective in wastewater treatment systems usually is the removal of carbonaceous material from the waste stream through growth of heterotrophic bacteria. The bacteria convert the energy of intramolecular bonds in the organic substrate to the high-energy phosphate bonds of adenosine triphosphate (ATP). This energy then is used to synthesize the various molecular components required for cell growth and reproduction. Energy conversion from substrate to ATP occurs via a series of oxidation-reduction reactions. The main ATP generation process within the cell is termed oxidative phosphorylation. ATP is generated as electrons removed from the substrate by oxidation are transferred along an electron transport chain to the terminal electron acceptor - oxygen in the aerobic activated sludge process. The overall process of *aerobic respiration* is depicted schematically in Fig. 1. A portion ($1-Y$) of the consumed substrate is oxidized to provide the energy required to reorganize the remainder (Y) of the substrate molecules into new bacterial cell mass.

Carbonaceous material removal and the related processes are not necessarily the only sinks for oxygen in activated sludge systems. Nitrification, which involves oxidation of ammonia nitrogen to nitrate nitrogen by autotrophic organisms, often will account for approximately 40 percent of the total oxygen demand.

The rate at which oxygen is consumed as an electron acceptor (i.e. the respiration rate) can be tracked with relative ease as the measurement involves easily monitored variables such as dissolved oxygen concentration or partial pressure of oxygen. This is not the case for certain important state variables such as active biomass concentration which cannot be measured directly. For this reason respirometry is a powerful alternative tool for assessing the condition of a system. In research and model development, respiration rate has been identified as the most sensitive parameter against which activated sludge theory can be tested. A number of experimental protocols based on respiration rate have evolved to isolate and study different aspects of process behaviour such as biomass growth rate and decay rate, nitrification rate, and hydrolysis. Also, respiration rate is the basis for a number of wastewater characterization protocols.

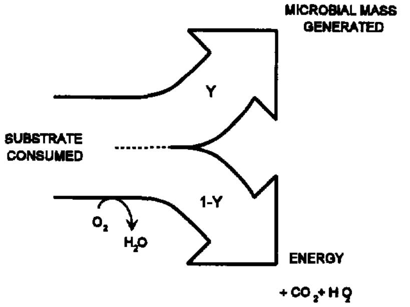


Figure 1. Schematic representation of substrate consumption process.

In an activated sludge system respiration rate and oxygen demand are related to all the aerobic organism activities, and vary in space and time. Many factors have an impact. These include: (1) the time-varying influent loading rate and the composition of the influent; (2) the flow regime in the system e.g. plug flow *versus* completely mixed; (3) the inclusion of unaerated zones for nutrient removal; (4) heterotrophic and autotrophic organism growth rates; (5) return activated sludge and mixed liquor recycle rates; (6) operating sludge age (or solids retention time); (7) the spatial distribution and efficiency of aeration devices. Because oxygen consumption is directly linked to process behaviour it is likely that respiration rate can be used as an effective tool in system control and for identifying disturbances which have an impact on process performance.

MEASURING PRINCIPLES

Respiration rate usually is 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) and (2) whether or not there is input and output of liquid and gas (flowing or static). The operation of all existing respirometers can be explained in terms of these criteria. Now, the principles will be discussed according to the phase where oxygen is measured.

Principles based on measuring DO concentration in the liquid phase

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. It is assumed that the DO concentration in the liquid phase can be measured. The DO mass balance over the liquid phase is:

$$\frac{d}{dt}(V_L C_L) = Q_{in} C_{L,in} - Q_{out} C_L + V_L K_L a_L (C_L^* - C_L) - V_L r \qquad (1)$$

where: C_L = DO concentration in the liquid phase
C_L^* = saturation DO concentration
$C_{L,in}$ = DO concentration in the liquid phase entering the system
$K_L a_L$ = 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 = respiration rate of the biomass in the liquid
V_L = volume of the liquid phase

Notice that, since it is a mass balance over the liquid phase, Eq. (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. Therefore, C_L must be measured and all other coefficients be known or neglected. In practice, the determination of r can be simplified in several ways.

One approach is to use a method without liquid flow and oxygen input. Then the first three terms on the right hand side of Eq. (1) fall away and the mass balance reduces to:

$$\frac{dC_L}{dt} = -r \tag{2}$$

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. The consequence of this approach is that the DO becomes exhausted after some time so that for each new measurement of r a reaeration is needed to bring the DO concentration to a higher level. DO and substrate are limiting when their concentrations become too low, causing a non-linear DO decrease. The procedure for the determination of r according to "Standard Methods" is based on this principle. The principle is often used for manually measuring r but it is also implemented in automatic respirometers which sample activated sludge from an aeration basin and do one or more measurements of the DO decrease. Generally, the principle is not practical for direct implementation in an aeration tank.

The disadvantage of the need for reaerations can be eliminated by continuously aerating the sludge. Then, the oxygen mass transfer term $K_La_L(C_L^*-C_L)$ must be included in the mass balance (Eq. 2). To obtain r both the differential term and the mass transfer term must be determined. To calculate the latter, the mass transfer coefficient (K_La_L) and the DO saturation concentration (C_L^*) must be known. These coefficients have to be determined regularly because they depend on environmental conditions such as temperature, barometric pressure and 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 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 at a constant DO concentration, thereby eliminating the dependency of r on the DO concentration (provided DO $\gg 0$ mg l^{-1}). This principle can be implemented in a separate respirometer or directly in the aeration tank.

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 is pumped continuously through a closed completely mixed or plug flow cell without gas phase. The liquid flow terms now have to be included in mass balance (2). Both DO concentrations $C_{L,in}$ and C_L must be measured continuously to allow the calculation of r. 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 the one explained in Eq. (2) and it is as such also sensitive to the effect of substrate and DO limitation. However, the effect of limiting substrate can be eliminated by the continuous addition of substrate (wastewater) to the respiration cell.

Principles based on measuring oxygen in the gas phase

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 (Eq. 1), a balance on the gas phase must be considered:

$$\frac{d}{dt}(V_GC_G) = F_{in}C_{Gin} - F_{out}C_G - V_LK_La_L(C_L^*-C_L) \tag{3}$$

where: C_G = O_2 concentration in the gas phase
$C_{G,in}$ = 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_L = volume of the liquid phase

The term $K_L a_L(C^*_L-C_L)$ represents the mass transfer rate of oxygen from the gas phase to the liquid phase and it comprises the connection between the two phases. Instead of measuring C_G directly, it can be related to volume or pressure changes by using the gas law. Additional assumptions to be made then are that the gas behaves ideally and that measured changes are only caused by changes in oxygen concentration. Because carbon dioxide is produced in the activated sludge process this gas must be absorbed chemically to avoid interference with the oxygen measurement.

From the mass balances (1) and (3) it follows that, in order to allow calculation of r, C_G must be measured and also knowledge of C_L is required. If mass transfer is sufficiently fast it can be assumed that the oxygen concentrations are in equilibrium so that the measurement in the gas phase is a good representation of the condition in the liquid phase. Especially in full scale situations where the aeration tank is used as a respirometer (off-gas or exhaust gas measurement), the validity of this assumption should be critically evaluated. In respirometers the measurement of r usually is simplified by operating under static liquid phase. In the simplest case, when both liquid and gas phase are static, 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. Another possibility is supplying oxygen from an external tank and measuring the amount of oxygen supplied, or generating the oxygen by electrolysis. The latter technique enables deduction of r from the electrolysis current. In both cases, temperature and pressure must be kept constant.

Table 1. Summary measuring principles respiration rate. The figures at the top schematically illustrate the different principles. Indicated are: the two phases gas (light) and liquid (dark), the flow regime of either phase (flowing or static) and the location where oxygen is measured (gas or liquid).

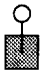
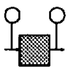
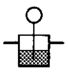
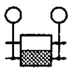
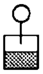
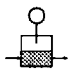
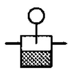
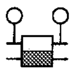
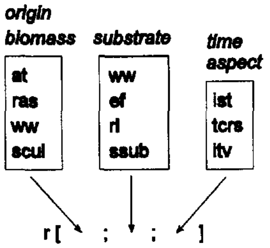
			measurement in liquid phase				measurement in gas phase			
	respirometric principle → process ↓									
liquid phase balance	respiration	$V_L r$	-1	-1	-1	-1	-1	-1	-1	-1
	dissolved oxygen accumulation	$\frac{d}{dt}(V_L C_L)$	-1	-1	-1	-1	-1	-1	-1	-1
	liquid flow	$Q_{in}C_{L,in}-Q_{out}C_L$		1		1		1		1
	gas exchange	$V_L K_L a_L(C_L^*-C_L)$			1	1	1	1	1	1
gas phase balance	gaseous oxygen accumulation	$\frac{d}{dt}(V_G C_G)$					-1	-1	-1	-1
	gas flow	$F_{in}C_{G,in}-F_{out}C_G$							1	1
	gas exchange	$V_L K_L a_L(C_L^*-C_L)$					-1	-1	-1	-1

Table 1 summarizes the measuring principles. The first column contains the names of the mass balance terms and the second column the mathematical equivalents. The succeeding columns list the respirometric principles, the first four being liquid phase principles the others being gas phase principles. The mass balances for each principle are formed by multiplying the terms with the coefficients in the column of the appropriate principle. The sum of all terms must equal zero.

MEASURED AND DEDUCED VARIABLES

Most measured variables do not need additional information to be interpreted (e.g. dissolved oxygen or nitrate concentration). For respirometry this is not the case. A respiration rate value or a percentage inhibition deduced from respiration rate measurements cannot be interpreted without additional information about some measurement attributes. Indeed, it may sometimes be rather difficult to consider a respirometer as a traditional sensor because it is a reactor in itself where different components are brought together to perform what may be called an "In-Sensor-Experiment" and in which the experimental conditions generally have a very large influence on the measurement results. The Task Group has 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 (Fig. 2). Below, some examples are given for these attributes to indicate the diversity of respiration rates that can be obtained from respirometers.



at	aeration tank	rl	return liquor
ras	return activated sludge	ssub	specific substrate
ww	wastewater	ist	instantaneous
scul	specific culture	tcrs	time course
ef	effluent	itv	interval

Figure 2. Nomenclature of respiration rate (see text for explanation).

Biomass

Several sources for the respirometer biomass exist: aeration tank, return activated sludge, wastewater from the treatment plant being monitored. While the choice of a 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 (e.g. pH, dissolved oxygen and substrate levels) will partly determine the result of the respirometric measurement. Hence, the sampling conditions are very important. The source of biomass also could be a specific culture grown separately, possibly on sewage or a synthetic substrate.

Substrate

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

Time aspect

As any measurement, respiration rate is a function of time. The measurement obtained with a respirometer can be presented in three modes: instantaneous, time course and interval. An instantaneous measurement assumes that the elapsed time between sampling and respiration rate measurement is zero, so that the initial condition is measured. A time course respiration rate measurement means that respiration rate in the respirometer is followed for some time in order to obtain a respirogram, i.e. a time series of respiration rate values. An interval type measurement denotes that a (single) relevant respiration rate measurement is obtained after a time interval in the respirometer.

Additional attributes

The concentration of substrate, like time aspect, is another important internal environmental condition that is crucial for the information content of the obtained measurement results. Three levels of substrate can be defined:

negligible, intermediate and excess. Negligible substrate levels may be obtained when no substrate is added intentionally or sufficient removal of substrate is guaranteed. It is expected or intended that the remaining substrate has no effect on the measured respiration rate. An intermediate level may be obtained if there is still a significant amount of substrate left in the sludge at the moment of sampling or if a determined amount of substrate is brought together with the sludge in the respirometer. A condition with excess substrate is characterized by the fact that a small change of substrate concentration has no effect on the measured respiration rate. In addition, specific components which 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 like pH, ionic strength and temperature are also important for the measurement result. However, these factors are usually not a part of the measurement strategy. They are assumed similar to the conditions in the treatment plant and kept or assumed constant or of no influence on the result.

Nomenclature

Respiration rate will be symbolically associated with the attributes presented above (Fig. 2). Examples are: The respiration rate measured immediately after sampling from a completely mixed aeration tank would be represented: *r[at;-;ist]*. If the sludge after sampling is aerated for a prolonged time in order to measure endogenous respiration rate, one would write: *r[at;-;itv]*. A respiration rate denoted *r[at1;ww;tcrs]* means the rate for sludge from the first compartment of an aeration tank in the presence of wastewater, measured for some time, i.e. a respirogram.

Deduced Variables

In process operation, control and research a biological interpretation is sought for the physically measured respiration rate. Therefore, the result of a respiration rate measurement frequently is converted to a deduced variable that is more appropriate for interpreting results in a particular context. Many deduced variables have been proposed. Most often simple calculations involving different types of respiration rates or involving respiration rate and other data lead to a deduced variable. Also, in recent years a number of sophisticated algorithms have evolved to deduce relevant variables. No detailed explanation of the underlying mathematics will be given here, though.

A few examples of deduced variables are given here. Specific oxygen uptake rate has been used as a measure of the loading condition of activated sludge. This is obtained by dividing respiration rate by biomass concentration. The percentage inhibition of the biomass due to a specific compound or a wastewater sample is another typical deduced variable. The required treatment time also can be assessed from respirometry, i.e. from a respirogram, the time needed to oxidize substrate can be found. Many methods have evolved to estimate influent substrate concentration. Similarly, the biomass concentration in samples can be assessed. In recent years, a lot of effort has been directed at estimating biokinetic parameters from respirometric measurements, e.g. growth rates, affinity and inhibition constants, etc. Similarly, attempts have been made to design respirometric measurements that allow characterization of the different fractions of wastewater in terms of the Activated Sludge Model No. 1 structure. In the final section, the application of these variables in control strategies for activated sludge processes is summarized briefly.

ELEMENTARY CONTROL CONCEPTS

A wastewater treatment plant is never at steady state, but is continuously subject to disturbances. The influent flow rate, composition and concentrations will vary significantly. Internal streams are purposefully or unintentionally changed. In an advanced nutrient removal plant there are many biological processes taking place simultaneously. Each one of these needs special operating conditions and reacts differently to the disturbances. One example is where carbonaceous removal and nitrification compete for dissolved oxygen.

In control it is crucial to define an objective, but this is not always stated explicitly. Typically, the *basic objective* is to keep the plant running, while meeting the effluent standards. The overall challenge often is to run the plant consistently despite all the disturbances, using measurement information and manipulated variables.

Often the coupling between the influent loading conditions and the effluent quality is extremely difficult to assess. Therefore it is important to define *operational objectives.* Given the adequate conditions, they will together guarantee a satisfactory final effluent. Typical operational objectives are: grow the right biomass population, maintain good mixing where appropriate, maintain adequate loading and DO concentration, maintain adequate airflow, favour good settling properties, avoid clarifier overload. The control problem is further complicated by the many couplings within the plant (caused by internal recycles) as well as to the sewer system. Also, there are couplings between water and sludge treatment. Many operational problems are related to fundamental biochemical/microbiological behaviour. The manipulated variables available often seem to be too limited to control the plant to some desired operating state.

Measurements are the basis for control. We have demonstrated that respirometers can add crucial information for the control of a treatment plant. All the variables that will influence the process are called inputs. Some of them can be manipulated, so they are called *manipulated variables.* Typical manipulated variables are: air flow rate, chemical dosage rate, waste flow rate and recycle flow rate. Other inputs will affect the process and are generated externally. As they cannot be manipulated from the process they are defined as *disturbances.* For example, the influent flow rate sometimes can be manipulated. If not, it is considered a disturbance. Some of the disturbances can be measured. A majority of the disturbances to a treatment plant are related to the influent, like the influent flow rate and concentration changes. Other disturbances are caused by the operation of other unit processes, like filter backwashing, or digester supernatant recycling. As long as they will influence the aerator behaviour they are all inputs to the aerator. The process is defined by state variables, typically concentrations of various substrate and organism types. Usually these cannot be directly measured. Instead, the process is observed by measurements that are related to the state variables. Both DO concentration and respiration rate (r) are examples of *measured variables.*

The standard feedback (FB) control scheme is depicted in Fig. 3(a). One or more measured variables are inputs to the controller and they are compared to *set point* (or reference) values. The purpose of the controller is to hold the measured variables as close as possible to the set point values, despite the disturbances. To illustrate the concepts, let us consider two control loops, DO control and respiration rate control. In traditional DO control, the DO concentration is measured and compared to a desired DO concentration (the set point). The air flow rate is manipulated so that the DO concentration would reach the desired value. Respiration is considered as a disturbance in this control scheme, since it is the reason for the DO concentration change. The control system does not recognize that r may be influenced by the air flow rate and does not explicitly take r into consideration. For example, assume that a toxic substance enters the plant. As a result r will drop. The DO controller will notice that less air will be needed to reach the DO set point value, but does not explicitly recognize the toxic disturbance. A decreasing substrate concentration would have caused the same control action. Consequently, such a control strategy needs to be complemented with more sophisticated measurements.

Now consider a respiration rate control system. The respiration rate is measured and compared with a desired r (the r set point). As in DO control, the air flow rate is manipulated so that the set point is reached. (Note that in this case the DO concentration will also be changed, but to some value that corresponds to the respiration rate.) Before, r was considered as a disturbance. Here it is the *controlled variable*, and the disturbances consist of e.g. substrate concentration changes, pH or toxic changes, that will cause r to change. Such a change is noticed directly in the measured variable. However, in this case one needs to make further analysis to exactly determine what is causing the change in r. The two examples above demonstrate that one has to define the boundary between controller and surroundings in each case, so that the inputs and disturbances are properly recognised.

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. The ideal is that the effect of the disturbance and the FF control action exactly cancel out, and there is no deviation from the set point. The basic design principle of a FF controller is illustrated in Fig 3 (b).

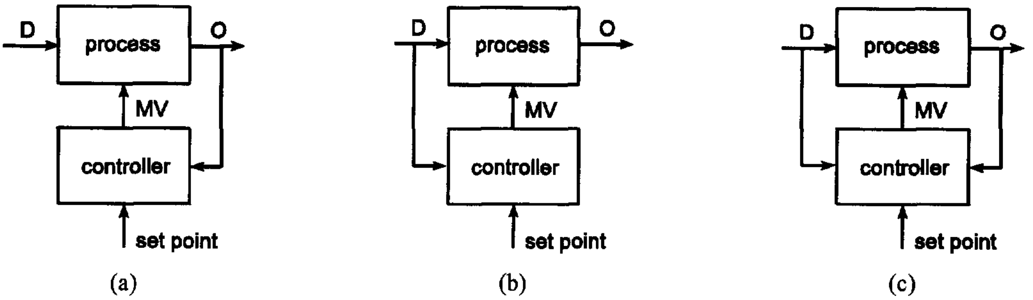


Figure 3. (a) Standard feedback control, (b) feedforward control and (c) feedforward-feedback control. D=disturbance, O=output, MV=manipulated variable.

It is obvious that a FF controller needs a method to calculate how much adjustment of the MV is required to cancel out the disturbances, i.e. a model is required. Since 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, like a sharp turn, an uphill road or a sudden obstacle, should be acted upon before they have influenced the car behaviour. The driver needs a good (mental) model of the car dynamics in order to compensate for such disturbances. It is not possible to completely cancel the influence of a disturbance with FF control, since the models and the measurements are not perfect. Therefore, it is always strongly recommended to combine a FF controller with a FB controller (Fig. 3 (c)).The FF controller makes a fast compensation for the disturbance, while the FB controller adjusts in a slower time scale. This is how response speed can be combined with accuracy.

RESPIROMETRY IN CONTROL

On the basis of a thorough literature review and personal communications, the authors have tried to provide an overview of existing proposals and applications of respirometry-based control strategies of the activated sludge process. It was felt paramount to classify the different attempts to support further development of activated sludge control systems that include respirometry. In the review all proposals were considered in which respiration rate was directly implicated in the control system and where sufficient explanation was given of its role. Both automatic and manual control were considered.

Classification of the strategies can be based on different elements of a respirometry-based control system, i.e. location of the respirometer, measured or deduced (input or output) variable, manipulated variable, controlled variable. For each of these elements, a number of possibilities were found in the literature and classifications could be based on any one characteristic. However, discussions clearly revealed that some classifications are more prone to confusion and misunderstanding than others and it was decided, and approved at the Copenhagen Specialised Conference on Sensors in 1995, that a classification based on the manipulated variable is the most appropriate since this variable is probably the easiest to identify in a control scheme.

The list of manipulated variables that have been proposed to act on the activated sludge process on the basis of respirometry encompasses most control handles available in current treatment plants. The authors have found references where flow rates of air, influent, return activated sludge, waste, sludge storage, internal nitrate recycle, chemical dosage, and sludge treatment return liquor are controlled using respirometry. In addition, there are examples where the influent distribution between reactors or bypass is manipulated based on respirometric measurements. In Table 2, examples are given for the five most common manipulated variables. For each of these examples the measured respiration rate and the variable deduced from this measurement are given. Next, the variable that is controlled by the manipulation, and the overall control structure (feedforward, feedback or a combination of the two) is given. The table attempts to reflect the diversity of control systems, rather than the most successful applications or being an exhaustive summary.

Table 2. Examples of respirometry-based control strategies. Nomenclature: see Fig. 2. "atn" means that the activated sludge comes from the last compartment of the aeration tank. "exc" is an additional attribute indicating excess substrate concentration.

Manipulated Variable	Measured Variable	Deduced Variable	Controlled Variable	Type
Influent flow rate	*r[scul;ww;ist]*	influent BOD	volumetric load	FF
	r[at1;ww;ist]	—	*r[at1;ww;ist]*	FB
	—	—	—	FF/FB
Return sludge flow rate	*r[at;-;ist], r[ras;-;ist]*	—	sludge load	FF
	r[at;-;ist]	biomass concentration	biomass concentration	FB
	r[at1;-;ist], r[atn;-;ist], r[ras;-;ist]	—	sludge load	FF/FB
Flow distribution	*r[scul;ww;tcrs], r[scul;ssub;tcrs]*	% inhibition	load with inhibitor	FF
	r[atn;-;ist]	specific respiration rate	specific respiration rate	FB
	—	—	—	FF/FB
Air flow rate	*r[atn;-;tcrs]*	effluent BOD	effluent BOD	FF
	r[atn;-;ist], r[atn;-;ist]	*r[atn;-;ist]/r[atn;-;ist]*	*r[atn;-;ist]/r[atn;-;ist]*	FB
	r[at;-;ist]	—	DO aeration tank	FF/FB
Waste flow rate	*r[at1;-;ist], r[ras;-;ist]*	—	sludge load	FF
	r[at;ww;ist;exc], r[at;ww;ist]	*r[at;ww;ist;exc]/r[at;ww;ist]*	*r[at;ww;ist;exc]/r[at;ww;ist]*	FB
	r[at;-;itv], r[at,ww;itv]	influent BOD	biomass conc., sl. bl. height	FF/FB

CONCLUSIONS

All measuring techniques for respiration rate can be classified into eight basic principles according to two criteria: (1) the phase where oxygen is measured, gas or liquid, and (2) the flow situation of either phase, flowing or static. At least three attributes must be specified to interpret respiration rate measurements: (1) biomass source, (2) type of substrate and (3) time aspect. The result of a respiration rate measurement often can be converted to a deduced variable. A classification of respirometry-based control strategies on the basis of manipulated variables is the most appropriate.