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TOWARDS A SIMULATION-BENCHMARK FOR EVALUATING RESPIROMETRY-BASED CONTROL STRATEGIES

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ABSTRACT

Many respirometry-based control strategies have been proposed in the literature but few successful practical implementations or even simulation-based evaluations have been reported. The state-of-the-art provides insufficient justification for the development of a how-to-do procedure for such control strategies in full scale. It is, therefore, expected that carefully conducted simulation studies will greatly support the evaluation of proposed strategies and, eventually, the implementation in practice. These studies should be based on a rigorous methodology including simulation model, plant layout, controller and test procedure. This paper describes the development of such a methodology, termed "benchmark". The benchmark is evaluated on the basis of a respirometry-based control strategy from the literature. Some simulation results are shown and modifications to the strategy imperative to the implementation in the benchmark are discussed. It is concluded that the benchmark provides a convenient means to perform a number of tests with the implemented control strategy. The benchmark should be further developed and tested.

KEYWORDS

Benchmark; control; cost function; modelling; respirometry; simulation.

INTRODUCTION

Many respirometry-based control strategies have been proposed in literature but few successful practical implementations or even simulation-based evaluations have been reported. This is 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 has hindered the introduction of respirometry-based control. Reported studies are often oriented towards either control theory or process technology and a realistic integration is usually not made.

In a respirometry-based control strategy the respiration rate itself may be used as a controlled variable. For example the actual rate in the aeration tank or the endogenous rate may be maintained at a certain value by manipulating one of the process input variables. However, often respirometry consists of the measurement of respiration rate under well defined experimental conditions with the purpose of extracting information with a particular biological significance. In these cases not respiration rate itself, but variables deduced from respiration rate measurements are used as controlled variables. The IAWQ-Task Group on respirometry in control of the activated sludge process has reported on the existing knowledge on respirometry-based control (Spanjers *et al.*, 1996). However, it is apparent that the state-of-the-art provides insufficient justification for the development of a how-to-do protocol for such control strategies and that more work is needed.

It is expected that carefully conducted simulation studies will greatly support the evaluation of proposed strategies, the possible development of new control strategies, and the implementation of these strategies. Such studies are facilitated by the availability of simulators for the activated sludge process. However, the availability of a control proposal and a simulator alone is not enough to evaluate the feasibility of a strategy. A uniform methodology is needed that includes a set of instructions to proceed from a proposal to an analysis of the performance.

The methodology as envisaged here may be termed "benchmark". This term is frequently used in computer technology to designate a performance measurement tool for hardware and software. Alternatively in benchmark studies, investigators are supplied with information on a particular system to be controlled, with the purpose to develop a controller for this system or to achieve a comparison between alternative control strategies. Graebe (1994) reports on an alternative benchmark study in which participants were invited to develop a control strategy for an unknown simulation model of a plant, which satisfied the required performance. Petersen (1992) used an activated sludge model to test control strategies. However, no efforts to standardize the procedure were reported in that paper.

In the context of this paper we define benchmark as: a methodology to test activated sludge process control strategies, consisting of a simulation model, a plant layout, a controller and a test procedure which provides a measure of performance. The objective of our study is to develop and employ such a benchmark for respirometry-based control strategies. It is important to note that our objective is not to compare different control strategies. The aim of this paper is to present the development of the benchmark. It must be stressed that the benchmark should not only comprise a simulation model but also a complete protocol of how to run the test and how to document the results. As part of this paper a first attempt to use the benchmark is made by selecting one strategy that is described in the literature (Stephenson *et al.*, 1981). The aim is not to evaluate the proposed strategy but to use it as an illustration of employing the benchmark.

This paper describes the development of the benchmark. First, some information is given about the simulation tools that were used for the development. The main part of the paper is a description of the development of the benchmark. The benchmark is evaluated on the basis of some simulation results. Finally, the results are placed in a broader context for the evaluation of respirometry-based control strategies and some issues for further work are addressed.

SIMULATION TOOLS

A number of dedicated and general purpose simulators are available, all with different characteristics (COST, 1995). The benchmark, however, must be independent of the simulation tool. Part of the development of the benchmark is a ringtest in which one and the same test should be done with different simulators. The simulators should have an interface for defining the plant layout and model (including parameters and initial states), for importing and exporting data, and for presenting the simulation results. Furthermore, a simulation tool must satisfy the following requirements in order to be suitable for benchmarking:

- able to handle a library of various plant layouts;
- allowing user defined models e.g. for respirometers;
- allowing incorporation of user defined controllers.

In this paper two simulators were used to develop the benchmark: GPS-X (Hydromantis Inc., Canada) and WEST (Hemmis NV, Belgium).

DEVELOPMENT OF THE BENCHMARK

In order for the benchmark itself to be generally accepted, there are a number of conditions which must be complied with. The benchmark should be:

- independent of simulation platform;
- based on a generally accepted simulation model;

- provide a test protocol;
- provide a measure of performance.

Bearing these requirements in mind a benchmark for respirometry-based control strategies was developed that consists of four units: simulation model, plant layout, controller and test protocol. For details on the underlying deliberations the reader is referred to Vanhooren and Nguyen (1996).

Simulation model

The simulation model is the whole set of mathematical equations and conventions which enables the simulation of a process, and consists of several subunits: process model, influent model, set of parameter values and set of initial values.

Process model

The Activated Sludge Model No. 1 (Henze *et al.*, 1987) was selected as the process model because it is widely recognized as a reasonable representation of the activated sludge process. Furthermore, it has been applied to numerous simulation studies and it is sufficiently detailed to describe respiration in most cases. The double exponential settling velocity model was selected for the secondary settling tank (Takács *et al.*, 1991). Most of the suggested parameter values for these models were adopted from the literature, but some parameters were modified according to recent experimental evidence (see section Parameter values set).

Influent model

The influent was designed to have a mean flow of 20,000 m^3d^{-1} and a total biodegradable COD of 300 mgl^{-1} for population equivalent of 100,000. Influent flow and pollutant concentrations were created by modifying actual plant loading data according to available knowledge of influent loading from literature (Longdong, 1994; Butler *et al.*, 1995; Verbanck, 1995; Campos and Von Sperling, 1996). The data were developed for a period of one week at 15 minute intervals. Seasonal variations were not considered because respirometry-based controllers act on a time scale of at most a few days. The influent data file may be requested from the authors.

Two scenario's were constructed: one for dry weather and one comprising of two storm events. Data for the latter were derived from Gujer *et al.* (1986), Lessard and Beck (1990), Bertrand-Krajewski *et al.* (1995), and Rouleau and Lessard (1996). Both datafiles, in ASCII comma delimited format, consist of a time series in the first column, all model concentrations in the subsequent columns and the influent flow in the last column. Fig. 1 shows one week of influent loading with storm events on Tuesday and Thursday. During these storm events the flow increases 3-fold. In the first storm the solubles decrease by 15%, while the total particulates increase 4-fold. For the Thursday storm event, the solubles are similarly diluted, but the particulates this time are decreased to half of the dry weather concentration. The reason the particulates are reduced during Thursday's storm is that the solids were washed out from the sewer during the first storm. During the weekend, flow and all concentrations are reduced by 15% from weekday loading.

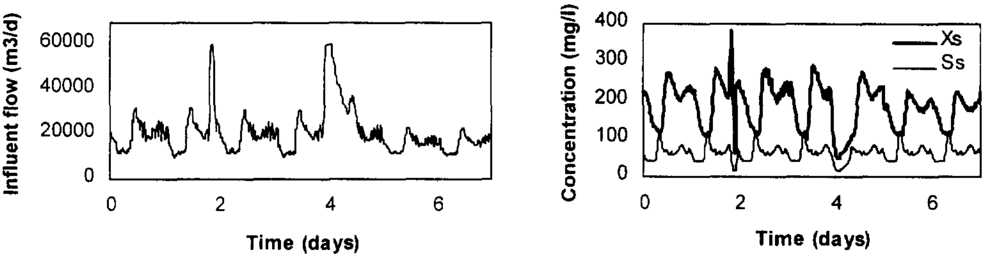

Fig. 1. Left: Influent flow. Right: Slowly biodegradable substrate X_S and readily biodegradable substrate S_S.

Parameter values set

Kinetic and stoichiometric parameters were selected by comparing the default values from the Activated Sludge

Models No. 1 and 2, and the simulators GPS-X and WEST. Furthermore, temperature dependent parameters were adjusted to a value corresponding with a temperature of 15°C by approximative linear interpolation. Settling parameters were obtained from the literature (Takács *et al.*, 1991) and recent experimental evidence (Vanderhasselt, 1996). The selected parameter values are presented in Table 1.

TABLE 1. Parameter values for the benchmark. For the nomenclature the reader is referred to the literature.

Kinetics			Stoichiometry			Switching functions		
μ_H	4	d^{-1}	gCOD/gVSS	1.48	-	K_{OH}	0.2	$g\ m^{-3}$
K_S	10	$g\ m^{-3}$	gVSS/gSS	0.9	-	K_{OA}	0.4	$g\ m^{-3}$
b_H	0.3	d^{-1}	gCOD/gSS	1.33	-	K_{NO}	0.5	$g\ m^{-3}$
η_h	0.5	-	Y_H	0.67	gCOD/gCOD			
η_g	0.8	-	Y_A	0.24	gCOD/gN			
k_h	3.0	d^{-1}	i_{XB}	0.08	gN/gCOD	Settling		
K_X	0.1	-	i_{XP}	0.06	gN/gCOD	v_0'	250	$m\ d^{-1}$
k_a	0.05	-	f_P	0.08		v_0	474.4008	$m\ d^{-1}$
μ_A	0.5	d^{-1}				r_h	0.000576	$m^3g^{-1}SS$
K_{NH}	1.0	$g\ m^{-3}$				r_P	0.00286	$m^3g^{-1}SS$
b_A	0.05	d^{-1}				f_{ns}	0.00228	-

Initial values set

As part of the test protocol for the benchmark, initial values for state variables must be established for the particular process model. It was decided that steady state values could be used as the initial values for the state variables. The respirometry-based controller is not implemented during the steady state analysis but the DO controllers are. Several methods exist for determining the steady state, such as overlaying state values from simulating several weeks or using a simulator built-in steady state solver. These methods may lead to different values.

TABLE 2. Possible process configurations for the benchmark.

Influent: 20,000 m^3d^{-1}, 300 gCOD m^{-3} Activated sludge: 4 kgMLSS m^{-3}		C-removal	C-removal/Nitrification	C- and N-removal
Wastage flow (m^3d^{-1})		500	250	270
Internal recycle flow (m^3d^{-1})		0	0	60,000
Compartment 1	Volume (m^3)	1000	2166	2666
	DO (g m^{-3})	2	2	0
Compartment 2	Volume (m^3)	1000	2166	2666
	DO (g m^{-3})	2	2	2
Compartment 3	Volume (m^3)	1000	2166	2666
	DO (g m^{-3})	2	2	2

Plant layout

A standard activated sludge plant was designed for carbon and nitrogen removal for the influent model described previously. The plant consists of an influent supply with a step feed possibility, three CSTRs in series and a circular secondary settler with a surface area of 800 m^2 and depth of 3 m. Wastage occurs from the bottom of the settler. The return sludge recycle ratio is one. Activated sludge may be recycled from the 3rd compartment to the first compartment. The three CSTRs allow for the flexibility to implement any of the following process configurations: C-removal, C-removal and nitrification, C- and N-removal (Table 2). The dissolved oxygen (DO) concentration is controlled in each tank individually. Once tuned, these DO controllers are considered to be a part of the plant layout.

Controller

Implementation of the respirometry-based controller

As previously explained the respiration rate itself or some other variable that is deduced from a respirometric experiment may act as the controlled variable. In a feedforward controller the controlled variable may even be another variable. At this stage in the development of the benchmark, only the respiration rate was used as the controlled variable in a feedback controller. If a numerical value of respiration rate is not available in the simulator, it can simply be calculated from the state and parameter values of the model as follows:

$$r = \frac{1 - Y_H}{Y_H} \frac{\mu_H S_S X_H}{K_S + S_S} + \frac{4.57 - Y_A}{Y_A} \frac{\mu_A S_{NH} X_A}{K_{NH} + S_{NH}}$$

In the benchmark, a feedback respiration rate controller was implemented in the simulator. This feedback controller was set up to minimize the difference between the set point respiration rate and the actual respiration rate measured in one of the three compartments by manipulating one of the process input variables. The controller was initially tuned according to the Cohen-Coon method (Stephanopoulos, 1984). The integral of the squared error (ISE) was used to measure the performance of the controller.

Implementation of the cost function

Once the controller is implemented and tuned, a cost function can be used to measure the performance of the plant under the respirometry-based control strategy. This cost function is a mathematical formulation which quantifies the main costs associated with wastewater treatment. Essentially, the costs should be a multi-objective function which includes effuent quality, energy costs, sludge production, wear of equipment, and risk of failure. At this stage of the benchmark, only the costs associated with effluent quality and energy consumption for aeration were considered. The cost function was modified from Vanrolleghem *et al.* (1996) and is expressed as follows:

$$F = U \left(k_{org}\, f(Q,SS,BOD_5,COD) + k_{nutr}\, f(Q,P,N) \right) + E\, f(K_L a)$$

where U is the pollution unit fine (capital yr^{-1}), E is the electricity cost (capital kWh), k_{org} and k_{nutr} are weighting factors for organic and nutrient pollution, $f(Q,SS,BOD_5,COD)$ is a function of the effluent organic load, $f(Q,P,N)$ is a function of the effluent nutrient load and $f(K_L a)$ is a function of the aeration power. The cost function is incorporated in the simulator in such a way that the cost values are calculated at each integration step.

Test protocol

The benchmark test involves five steps.

1. Selection of the process configuration

The appropriate process configuration (C-removal, C-removal and nitrification or C-and N-removal) is selected according to Table 2.

2. Implementation of the respirometry-based control strategy

This consists of simply selecting the controlled variable (i.e. the respiration rate) in one of the three compartments, a process input variable as the manipulated variable and activating the standard P(ID) controller. Default control parameter values may be used initially to run the controller.

3. Establishing initial values

Steady state values may be used as the initial values for the state variables.

4. Tuning of the controller

There are many tuning methods documented in literature. Some examples are Ciancone correlations (Marlin, 1995) and Cohen and Coon method (Stephanopoulos, 1984). These tuning methods identify initial values for the control parameters. Most tuning methods require a simplified dynamic model of the open-loop process. For the benchmark, the dynamic model may be determined by obtaining the transient open-loop response of the controlled variable (i.e. with the controller disabled) to a step change in the manipulated variable. This simulation is performed under constant influent flow and pollutant loading conditions (i.e. 20,000 m^3d^{-1} and COD of 300 $mgCODl^{-1}$, respectively).

The initial values obtained from the tuning methods must then be adjusted until acceptable control performance is achieved. This step is often referred to as fine-tuning. Marlin (1995) recommends obtaining the response of the controller to a set point change to determine whether the tuning is satisfactory. For the benchmark, fine-tuning can be performed under variable loading conditions and subjecting the controller to set point changes. The control parameters may then be further fine-tuned by adjusting their values until the integral of the squared error between the set point and the measured controlled variable is minimized.

5. Evaluation of the control strategy

The performance of the control system may be evaluated by subjecting the controller to various input disturbances. For the benchmark, these disturbances include changes in the manipulated variable and set point, diurnal influent loading (for dry weather and storm events), and sinusoidal influent loading. The performance of the controller under such disturbances may be evaluated on the basis of the following tests:

1. The response of the respiration rate to a step change in the manipulated variable is observed for the uncontrolled system receiving constant influent. From the response curve the dynamics of the uncontrolled system are assessed by calculating such parameters as steady-state gain, time constant and dead time.
2. The response of the respiration rate to a step change in the set point is observed for the controlled system receiving constant influent. From this test, important measures of performance, such as integral error, maximum deviation of the controlled variable, maximum overshoot of the manipulated variable, decay ratio, rise time, settling time, etc. may be obtained.
3. The response of the controller to variable loading conditions is observed. The above measures of performance may also be calculated to assess the controller.
4. A closed-loop frequency response may also be used to assess the performance of the controller. Frequency response calculates the system output in response to a sine input. The measure of control performance obtained from this analysis is the amplitude ratio of the controlled variable, which can be considered to be the deviation from the set point.
5. During a fixed simulation period and varying influent flow and concentrations the controlled variable is observed for the controlled system subject to various set points. The resulting cost function is evaluated and from the respiration rate the integral of the squared error is calculated.

EVALUATION BENCHMARK

The respirometry-based control strategy proposed and applied by Stephenson *et al.* (1981) was selected to illustrate the use of the benchmark. In this control strategy the wastage flow was manipulated to maintain the endogenous respiration rate of the sludge in the aeration tank at a set point value. Respiration rate was calculated from the dissolved oxygen mass balance over the aeration tank assuming a known mass transfer coefficient. The underlying idea of the strategy is that endogenous respiration rate is representative of the active biomass concentration. An optimum set point for the respiration rate was selected such that an appropriate biomass concentration and hence an adequate process performance was guaranteed. To ensure that control was based on measurement of endogenous respiration rate, the controller was only active during low loading periods (3:00-8:00 h) when the concentration of substrate in the aeration tank was negligible. During this period the automatic controller activated the constant speed wastage pump as long as the measured rate was above the set point.

The above strategy was implemented in the benchmark. In the work of Stephenson *et al.* (1981) nitrification was not reported, so a C-removal configuration was selected (Table 1). Respiration rate in the 3rd compartment and wastage flow from the settler were selected as the controlled variable and the manipulated variable, respectively. It was assumed that the respiration rate in the 3rd compartment was equivalent with the endogenous rate measured during low loading periods in the case of Stephenson *et al.* Contrary to that case the controller was continuously active in the benchmark. Tuning of the controller was not straightforward and heuristic methods proved to be necessary. These consisted of trial and error, and evaluation of overshoot and oscillation of respiration rate with changing controller parameters.

Approximately, the simulation results are in agreement with the observations by Stephenson *et al.* (1981) although a number of differences in performance of the controlled treatment plant exist. Yet, it appeared that the benchmark provides a convenient means to perform a number of tests with the implemented control strategy. For example, since for this particular control strategy it is imperative that the true endogenous respiration rate is measured (no substrate present), this condition can easily be checked by observing the readily biodegradable substrate concentration S_S. An example of a simulation run is depicted in Fig. 2. Rather large fluctuations of the respiration rate around the set point can be observed.

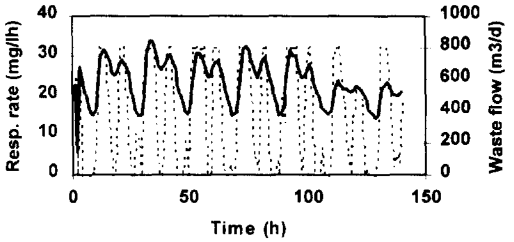

Fig. 2. Respiration rate (solid line) controlled by manipulating waste flow (dashed line). Set point 22 mg l^{-1}h^{-1}.

DISCUSSION

The control strategy used in the benchmark is a different, more general one than the strategy developed by Stephenson *et al.* (1981). Moreover, the influent characteristics and the plant layout are not exactly the same. The most important differences are summarised in Table 3.

TABLE 3. Differences between Stephenson *et al.* (1981) and the benchmark in this study.

Aspect	Stephenson *et al.* (1981)	Benchmark
number of aeration tanks	1	3
variability loading	low	high
location respiration measurement	in the sole tank	in 3rd tank
wastage rate	fixed rate during low loading	continuous and variable
type of controller	on/off feedback	P(ID) feedback

An important difference between the benchmark layout and the layout used by Stephenson *et al.* is that the latter used a one-compartment reactor. It is believed that this does not affect the general process performance. However, the three compartment reactor imposes a decision on the location of the respiration measurement, which may in turn affect the performance of the controller. Also the different kind of controllers, as described previously, may affect the performance. The benchmark should be as general as possible in order to allow an objective comparison between different control strategies. Therefore, the benchmark units simulation model, plant lay out and controller are preserved and rather the case to be evaluated is modified. However, it should be checked if these generalizations are allowed by performing simulations with the exact case.

In this paper only one particular control strategy is addressed. In the next stage other proposed respirometry-based control strategies will be tried to test and further refine the benchmark. Once the benchmark proves to be a useful testing tool it may provide a framework to explore proposed respirometry-based control strategies that are promising and possibly to develop new strategies.

At this stage perfect respiration rate measurements are assumed. In the next phase of the study models of respirometers (e.g. Giroux *et al.*, 1995) will be included and measuring noise will be imposed on the respiration rate to assess the impact of imperfect measurements on the controller performance. Respirometry often involves more than just measuring the value of the respiration rate at a particular location and time: carefully conducted respirometric experiments under well defined conditions allow the extraction of other (deduced) variables which can be used as a basis for process control, such as BOD and maximum nitrification rate. These respirometric experiments also will be included in the benchmark.

This research focuses on the development of a benchmark for respirometry-based control strategies. Therefore, the primary measured variable is the respiration rate. However, the methodology may be expanded later to cover other measurable variables in the activated sludge process.

CONCLUSIONS

A benchmark for evaluating respirometry-based control strategies has been developed which consists of four units: simulation model, plant layout, controller and test protocol. A strategy was selected to illustrate the use of the benchmark, and it is concluded that the benchmark provides a convenient means to perform a number of tests with this strategy. Because the developed benchmark is as universal as possible, a number of differences between the benchmark and the strategy to be evaluated are inevitable. It should be checked if the generalizations are allowed. The benchmark should be further developed and tested.

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