Design and interpretation of dedicated experiments for hydraulics and biokinetic characterisation of an industrial activated sludge system.

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ABSTRACT

A dedicated three-week measuring campaign at a full-scale industrial wastewater treatment plant was carried out to obtain basic information for a full-scale model. Modelling was used to interprete the results. First a tracer test was performed to determine the hydraulics. It was concluded based on modelling that the hydraulics of the system could be described by two tanks in series with non equal volume. The influent and recycle flows were found to be unequally distributed to the reactors. Secondly, a methodology is illustrated of how to characterise the wastewater and sludge kinetics from respirometric batch experiments by modelling. Two wastewaters were studied and it was concluded that the same model structure could be applied and that the kinetic parameters were comparable.

INTRODUCTION

During the last decades the effluent standards that both municipal and industrial wastewater treatment plants (WWTP) have to comply with, have become increasingly stringent. This has increased the demand for more model-based analyses and advanced control strategies with the aim of optimising the plant performace. The first and very crucial step for successful development of control strategies is to build a mathematical model of the full-scale WWTP. However, the quality of the model predictions depends highly on a reliable calibration of the model. For that purpose information about the hydraulics together with detailed knowledge of the wastewater characteristics and biokinetics of the sludge are required. Especially for industrial WWTP this information may be very plant specific due to the higher variability of industrial wastewater compared to municipal wastewater.

To identify the flow distribution in aeraton systems a tracer experiment can be performed. The tracer is a soluble substance not adsorbing to the biomass, and as such a faithful marker of the transport processes of dissolved components inside the reactor. From the response on the tracer input Residence Time Distribution (RTD) curves can be derived which can be used to obtain the essential hydraulic information. There are several types of models accounting for flow patterns, but dealing with activated sludge reactors one model is most common. This model is called the n-tanks-in-series model and describes the phenomenon of dispersion in a flow by means of a series of ideally stirred tanks. The behaviour of n stirred tanks in series ranges from perfect mixing to plug flow.

The composition of organic matter in wastewater is traditionally characterised by daily analysis of the Chemical Oxygen Demand (COD) of non-filtered and filtered wastewater samples, i.e. total- and soluble-COD. Additional analysis of the Biological Oxygen Demand (BOD) gives information about the biodegradability of the wastewater. Traditionally the wastewater is analysed for the Biological Oxygen Demand required over 5 days (BOD5). The information obtained from daily samples may however not always be sufficient for model calibration, since the information about the diurnal changes of the wastewater may be lost. Via respirometry, however, the short-term BOD (BODst) can easily be monitored on-line to achieve information about the diurnal dynamics of the wastewater characteristics (Vanrolleghem, 1994).

The respirograms retrieved on-line can be interpreted in detail using a mathematical model. The models most often used to describe the biological processes in activated sludge are the Activated Sludge Models No. 1 and 2 (Henze *et al.*,1987 and Henze *et al.*,1995). However, these models were developed and are able to describe with minor adjustments the behaviour of systems treating municipal wastewater with only minor impact from industrial discharges. If the same models are to be applied to industrial WWTP a more extensive model calibration is required.

Methods that automatically can find the most appropriate model for a description of wastewater characteristics and biokinetics from respirograms are still not available except for some simple cases (Vanrolleghem and Van Daele, 1994). Therefore, dedicated batch experiments have first to be carried out off-line to find the most appropriate model structure. This model can then be applied for interpretation of the on-line data. Combined with the results of the hydraulic study a full-scale model can subsequently be built and used for optimisation of the WWTP.

In this study a three-week intensive measuring campaign at a full-scale industrial WWTP was carried out to obtain basic information for a full-scale model of the activated sludge processes. The WWTP under study removed COD only. Often COD remains the main problem in industrial wastewater treatment plants.

In this paper it is illustrated how modelling can be used to obtain the detailed basic information required for building a full-scale model. First, attention is paid to the experiments and modelling carried out to determine the hydraulics. Second the methodology of how to find a model structure for the wastewater characteristics and sludge biokinetics from off-line batch experiments is illustrated.

HYDRAULICS

MATERIALS AND METHODS

A tracer test was performed at the industrial WWTP. The plant consists of three parallel activated sludge reactors with a volume of 1930 m^3 (AS1), 3050 m^3 (AS2) and 3050 m^3 (AS3) and one rectangular settler. Return sludge and influent are mixed in a small distribution tank before distribution to the three bioreactors. The total influent and recycle flow to the activated sludge system was measured, but the distribution of influent and recycle flow to the 3 reactors was not known. As a tracer lithium chloride was used. A pulse of 20 kg of LiCl was dosed in the distribution tank. Figure 1.a shows a schematic representation of the WWTP with indication of the LiCl dosing point and the different sampling points.

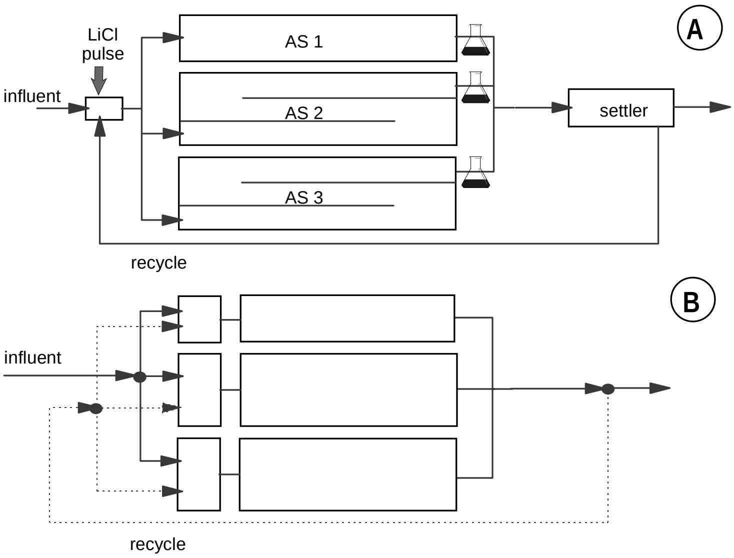

Figure 1 *a/ Schematic representation of the industrial WWTP.*
b/ Model representation of the industrial WWTP.

RESULTS AND DISCUSSION

Figure 2 shows the results of the tracer experiment.

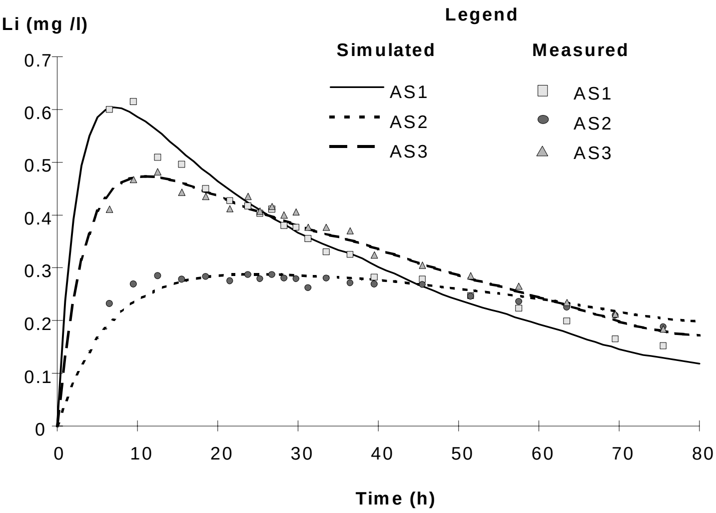

Fig. 2 *Measured and simulated results of the tracer experiment.*

The conversion of the experimental results into RTD curves is complicated because the effluent concentration of Li in the three activated sludge reactors are coupled due to the sludge recycle flow. Halting the sludge recycle during the tracer experiment was not feasible because sludge would be lost to the effluent. Moreover, the sludge recycle flow is affecting the hydraulic flow pattern of the bioreactors. It was decided to simulate the tracer test and as such obtain the hydraulic information of the reactors. In this model each activated sludge tank was represented by an a priori unknown number of completely mixed tanks in series.

Assuming the same flow fractions of influent and recycle to the three tanks, the model was not able to fit the experimental concentration curves. This pointed to the fact that mixing of influent and recycle in the distribution box is not perfect.

Consequently, the imperfect mixing in the distribution box was modelled by assuming that the three reactors each received different fractions of the influent and the recycle flow (Figure 1.b). By means of additional information on sludge concentrations in the three tanks and in the return liquor mass balances for the sludge concentration could be written. From the tracer experiment too mass balances for the tracer concentration were derived. Solving this set of algebraic equations revealed the flow distribution of influent and recycle to the three tanks. This method for calculation of the distribution didn't make use of the modelling of the tracer experiment nor any simulation result. It could be concluded that the distribution of the influent to each reactor was not proportional to its volume, resulting in different volumetric loading rates.

Using this fixed influent and recycle distribution the tracer experiment was simulated. Fitting of the simulation results to the experimental curves was performed by adaptation of two parameters :

- The number of completely mixed tanks in series to describe the hydraulics of each reactor;
- The total active volume of the three reactors.

Assuming the completely mixed tanks had equal volume, the best fit to the experimental results was obtained by describing the hydraulics with two tanks in series. This fit could be improved by allowing the two tanks to have non equal volume, as shown in Figure 1.b. The flow pattern in the reactor is described by the hydraulic model of a small tank (10% of reactor volume) followed by a larger tank. Theoretically, also the opposite setup - a large tank followed by a small tank - would yield the same results. But in view of the more intense mixing in the beginning of the reactor a small tank followed by a large tank is the most plausible. Finally, the active volume of the activated sludge system had to be reduced with 15 % compared to the total reactor volume. This may be explained by build-up of settled material or alternatively a considerable gas holdup. Indeed, literature data on gas holdup in bubble columns showed that typically gas void fractions in bioreactors, depending on air rate and flow regime, vary between 0.07 and 0.25 (Heijnen and Van 't Riet, 1984).

CHARACTERISATION OF WASTEWATER AND SLUDGE BIOKINETICS

MATERIALS AND METHODS

The off-line batch experiments were carried out with a RODTOX device (Kelma bvba, Niel, Belgium) installed in the lab. The RODTOX consists of a constantly aerated completely mixed batch reactor containing 10 litre of sludge, for a more detailed description of the principles see Vanrolleghem. (1994). The dissolved oxygen (DO) concentration, from which the respiration rate is obtained, is measured by a DO electrode and collected on a PC. Temperature is controlled at 25^{o}C and the pH at 7.5. Experiments were carried out with sludge sampled from the activated sludge tanks at the full-scale plant and with two different influent samples. Acetate was the calibration solution.

RESULTS AND DISCUSSION

In the following the data analysis will be described and discussed.

Figure 3 shows one example of the DO concentration as function of time for one of the two off-line batch experiments with wastewater samples.

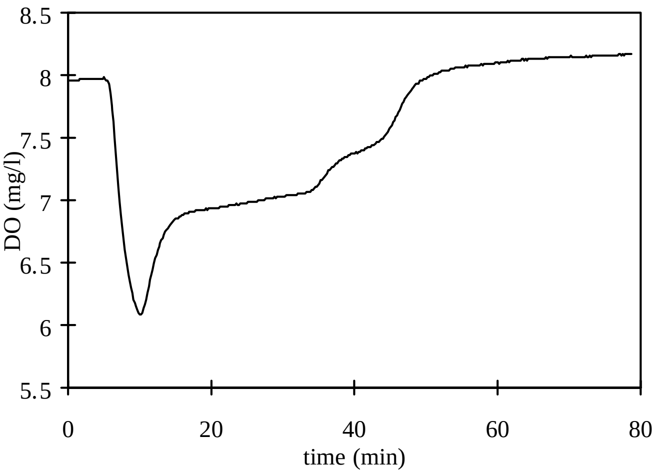

Figure 3 *Dissolved oxygen (DO) as function of time*

The DO profiles can be described by (Vanrolleghem *et al.*, 1994):

$$\frac{dC}{dt} = K_La \cdot (Ce - C) - OURex \quad (1)$$

where Ce is the equilibrium DO concentration, K_La the mass transfer coefficient of oxygen and OURex the temporary supplemental oxygen uptake rate caused by oxidation of the wastewater. OURex can then be determined by (1) if K_La and Ce are known. Using the DO profiles of the calibrations K_La and Ce were estimated by non-linear estimation (Vanrolleghem, 1994). Figure 4 and 5 show the resulting OURex as function of time, also called a respirogram (the data are shown together with the model fit, see below).

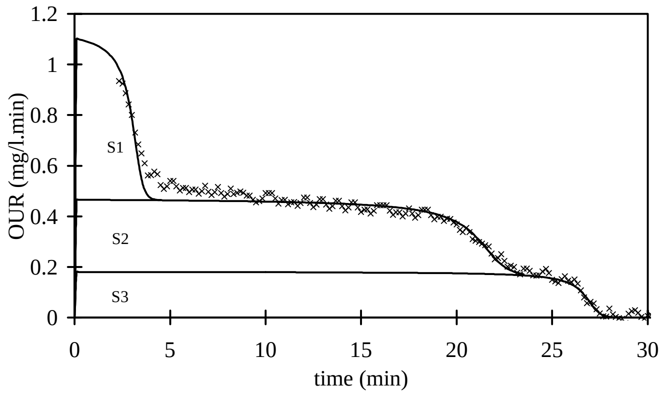

Figure 4 *Oxygen Ulitisation Rate (OUR) as function of time for sample 1.*

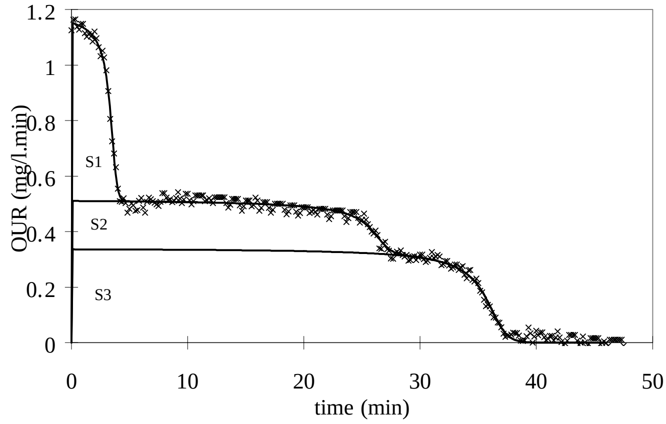

Figure 5 *Oxygen Ulitisation Rate (OUR) as function of time for sample 1.*

In Figure 4 and 5 three distinctive shoulders can clearly be seen. The shape of the respirograms indicates that the organics in the wastewater can be divided into three fractions since the shoulders end in a distinguisable sharp way (Vanrolleghem and Van Daele, 1994). A sharp shoulder corresponds to a high affinity for the substrate, i.e. the degradation of substrate takes place at maximum rate until the substrate concentration is very low and then it suddenly stops. The model built for bio-kinetic characterisation of the process includes COD removal only and was a modified version of the Activated Sludge Model No.1 (ASM1) (Henze *et al.*,1987). ASM1 is based on Monod kinetics and fractionation of the biodegradable organic substrate into soluble readily biodegradable substrate and particulate hydrolysable substrate. In this case, the soluble readily biodegradable substrate was divided into three fractions (S_1, S_2 and S_3).

The same model structure was applied to both wastewater samples. However due to the lack of data points for wastewater 2 the first "shoulder" of the respirogram could not be properly estimated. Thus the parameters were fixed on the values derived from wastewater 1. A simple single Monod model was fitted to the results of the addition of calibration solution (acetate). In Tables 1 and 2 the estimated parameters for the bio-kinetics of the sludge with calibration solution and wastewater are listed. Table 3 shows the estimated wastewater fractions (S_1, S_2 and S_3) together with the concentrations of total- and soluble COD and VFA measured by standard lab analyses.

calibration	μ	K
1	4.8	0.24
2	5.2	0.43

Table 1 *Estimated kinetic parameters for calibration solution half saturation concentration K is in mgCOD/l and μ is in d^{-1}.*

sample	μ_1	K_1	μ_2	K_2	μ_3 (d^{-1})	K_3
1	3.93	0.37	1.97	0.57	1.02	0.27
2	(3.93)	(0.37)	1.68	0.36	0.96	0.13

Table 2 *Estimated kinetic parameters for wastewater samples, half saturation concentration K is in mgCOD/l and μ is in d^{-1}.*

The kinetic parameters of the two wastewater samples are comparable indicating that the wastewater fractions are similar. In Figure 4 and 5 the model fits are shown. Separate simulations were performed to illustrate the contribution to the respirogram of each substrate.

sample	S_1	S_2	S_3	$\sum S$	CODt	CODs	VFA
1	158	1348	504	2010	3624	3446	113
2	205	656	533	1394	1921	1604	123

Table 3 *Estimated and measured COD and VFA concentrations (mg/l) in the wastewater.*

The estimated sums of substrates are in both cases reasonable comparable with the measured COD concentrations. The difference is probably due to the fraction of the wastewater which is not readily biodegraded within the time frame of the batch experiments or is inert. The estimated kinetics of the calibration solutions indicate that substrate 1 (S_1) is acetate-like. This is confirmed by the VFA analysis (Table 3).

CONCLUSION

In this paper it was illustrated, how detailed basic information required for building a full-scale model of a WWTP, can be found by the use of modelling.

A tracer test was performed at the full scale WWTP to allow for the determination of the hydraulics of the bioreactors. The effluent concentrations of the three parallel bioreactors are coupled by means of the sludge recycle. Therefore, hydraulics of the activated sludge reactors can not be derived directly but the tracer data had to be interpreted by the use of modelling. The hydraulics of each bioreactor were modelled by two completely mixed tanks in series with non equal volume. The active volume of the reactor seemed to be 15 % lower than the total reactor volume. This may be explained by the result of gas holdup.

Respirometric batch experiments were carried out off-line to determine a model structure for description of the wastewater characteristics and biokinetics. It was found that the same model structure could be applied to the two wastewater samples under study and that the kinetic parameters were comparable. Moreover it was found that both wastewaters could be fractionated into three fractions albeit in different amounts, and that one of the fractions was acetate-like.

LITERATURE

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