Monitoring and modelling a pilot-scale trickling filter using on-line off-gas analysis

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Abstract The process characteristics of a pilot-scale trickling filter system were quantified by means of a measurement campaign with the use of off-gas analysis. A load shift experiment was conducted in which the influent load to the trickling filter system was suddenly decreased. To model the biodegradation in the filters, the model developed by Rauch *et al.* (1999) was used. This model was extended with equations for the production and the pH-dependent liquid phase equilibrium for inorganic carbon (IC).
Keywords Biofilm; mathematical modelling; off-gas analysis; trickling filter

Introduction

The filter system under study is a pilot-scale trickling filter in which non-invasive measurement techniques were evaluated for use in calibration of models for process optimisation. The design of the filter unit was made such that it would allow a full characterisation of the relevant model parameters, and an easy monitoring of the system's performance only using measurements of inflow and outflow. Among other measurements, the off-gas was continuously monitored for CO_2 and O_2.

The filter unit's dimensions were chosen to represent a cylindrical core taken from a full-scale unit. Practical considerations limited the depth to 1.8 m. To ensure uniform conditions throughout the filter and to allow quantification of specific surface area and biofilm parameters, a plastic carrier medium was used. Its specific surface area is 220 m^2/m^3. As influent to the trickling filter plant, a synthetic sewage was used which mimics real domestic wastewater. The composition of the sewage is based on the Syntho medium (Boeije *et al.,* 1998). In practice, the influent is prepared as a concentrated liquid (20x or 30x), and was diluted with tap water when it was pumped into the filter set-up.

Measurement Techniques

Measurements of COD, SS, N and P were done using standard techniques. For the measurement of O_2 and CO_2 in the gas phase, paramagnetic and infrared measurement techniques were used. The composition of the off-gasses of biological wastewater treatment systems, in terms of oxygen and carbon dioxide, is the result of complex interactions between the biodegradation activity of the biomass and the distribution of these substances over the liquid and the gas phase in the reactor. The oxygen uptake rate (OUR) and the carbon dioxide production rate (CPR) can be derived theoretically from the reactions that describe carbon removal, nitrification and denitrification. The CPR is, however, not directly measurable. The dynamic equilibria in which CO_2 plays a role result in a distribution of CO_2 over the liquid and the gas phase so that not the CPR but rather a CTR (CO_2 transfer rate) is measured in the gas phase as represented in the following figure (Noorman *et al.,* 1992; Govind *et al.,* 1997). As a consequence, quite some microbially produced CO_2 can leave the system in the water and not in the gas phase.

$$\begin{array}{ccccccc} CTR^{measured} & & & & CPR^{reality} & & \\ \uparrow & & & & \downarrow & & \\ CO_2{}^{(gas} \leftrightarrows CO_2{}^{(aq)} & \leftrightarrows & H_2CO_3 & \leftrightarrows & HCO_3^- + H^+ & \leftrightarrows & CO_3^{2-} + 2H^+ \end{array} \quad (1)$$

The measurement of OUR is less subject to these phenomena because oxygen can not accumulate in the water phase to the same extent as inorganic carbon.

Off-gas measurement methods are robust, accurate, relatively cheap and widespread in the fermentation industry. However, because of the phenomena explained above, a single measurement of the CO_2 concentration in the off-gasses of the filter is not sufficient to describe the inorganic carbon (IC) equilibrium. Extra measurements of the IC concentration and the pH are needed. This was done using the titration technique developed by Van Vooren *et al.* (1999). Titration curves are monitored by adding a 0.1 M HCl solution to lower the pH from the actual pH of the sample, down to pH 2.5. Software developed in C++ calculates the buffer capacity profiles from the titration curves and estimates the IC concentration

from them. Once the total concentration is determined, the partitioning of the forms CO_3^{2-}, HCO_3^- and $CO_{2,aq}$ can be determined using a model in function of the actual pH of the sample.

Furthermore, when estimating the CPR from the measured CTR, a value for the volumetric transfer coefficient is needed (Hellinga *et al*., 1996). It can be estimated assuming that the K_La values of oxygen and CO_2 can be related by their respective diffusion coefficients (Noorman *et al*., 1992; De heyder *et al*., 1997).

$$K_L a_{O_2} = \sqrt{\frac{D_{O_2}}{D_{CO_2}}} K_L a_{O_2} \qquad (2)$$

where D_{O_2/CO_2} are the liquid diffusion coefficients of O_2 resp. CO_2.

Measurement results

A load shift experiment was conducted in which the influent load to the pilot-scale trickling filter system was suddenly decreased. It is clear that the off-gas O_2 concentration increases and the CO_2 concentration dropped after the load shift (Table 1 and Figure 1). The drop of the O_2 concentration was clearly caused by a decreased activity of the heterotrophic biomass, slightly compensated by an increased activity of the autotrophic biomass using CO_2 as a carbon source. A start-up of the nitrification activity could be seen in the filter at low load. A decrease of the ammonium concentration and an increase of the nitrate concentration was noticed (Figure 1).

Table 1. Averaged off-gas concentrations at high and low loading conditions (vol%)

	CO_2	O_2
High load (before load shift)	0.56	20.27
Low load (after load shift)	0.15	20.77

Model building

To describe the load shift, a simple dynamic model was used for fast simulation of the removal of multiple substrates by different bacterial species growing in a biofilm reactor (Rauch *et al.,* 1999). The model is an extension to the half-order reaction concept that combines a zero order kinetic dependency on substrate concentration with diffusion limitation. The idea behind this model implementation is to decouple the calculations of the two major processes in the biofilm: substrate diffusion and biochemical conversion. This is done by means of a two step procedure where (1) for each conversion process that is influenced by diffusion, the active fraction of the biomass within the biofilm is computed by means of a simple analytical solution and (2) all conversions within the biofilm are calculated as if the biofilm were an ideally mixed reactor but with only the active fraction of the species contributing.

This model was extended with a model for the description of the production and exchange of CO_2 in the biofilm reactor based on the model developed by Spérandio and Paul (1997). To describe the off-gas measurements in the model, a gas phase compartment had to be included. The gas phase was modelled as one single mixed tank. Figure 2 shows the layout of the filter in the WEST simulator. The number of tanks (7 in series) describing the liquid phase in the reactor and their respective volumes were determined using a tracer test described in Vanhooren *et al.* (1999).

Starting from a standard parameter set (Vanhooren, 2001), some parameter adjustments needed to be done. The oxygen transfer from the gas phase to the water had to be adjusted so as to provide the biomass with enough oxygen to degrade the substrate. A K_La value of 2700 d^{-1} was incorporated for O_2, the K_La for CO_2 was derived from this value (equation 2) and was set to 2430 d^{-1}. The results from the above manipulation is that during the high loading period, an oxygen limited regime was established in the upper five tanks of the filter. The simulated off-gas O_2 concentration was 20.28 vol%, the CO_2 concentration in the simulations was 0.54 vol%. These values agree very well with the measurement results (Table 1). Also the simulated outflow total COD concentration agreed well with the measurement results.

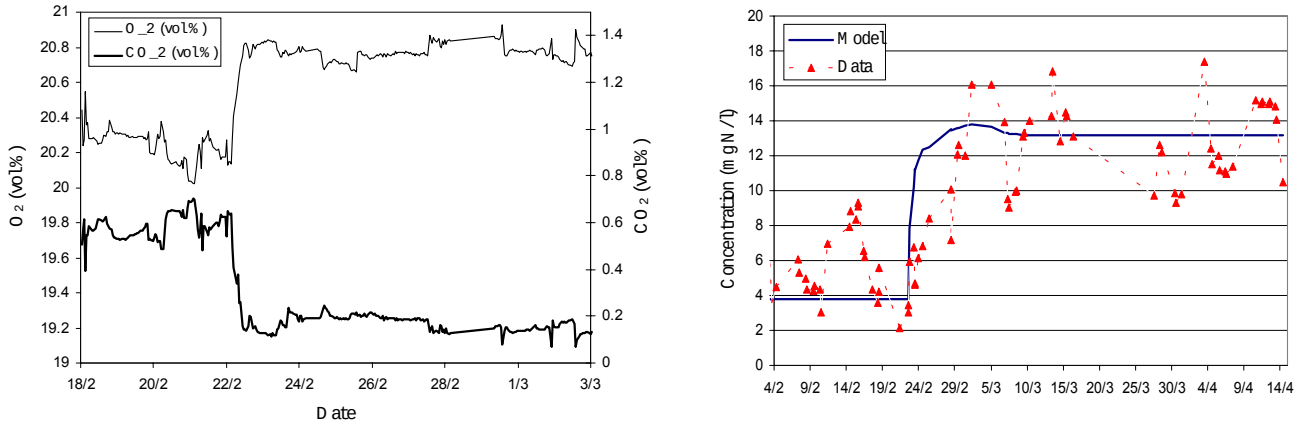

Figure 1 On-line measurement results of the O_2 and CO_2 concentrations in the filter's off-gas during the load shift (left) and measured and simulated nitrate nitrogen before and after the load shift (right).

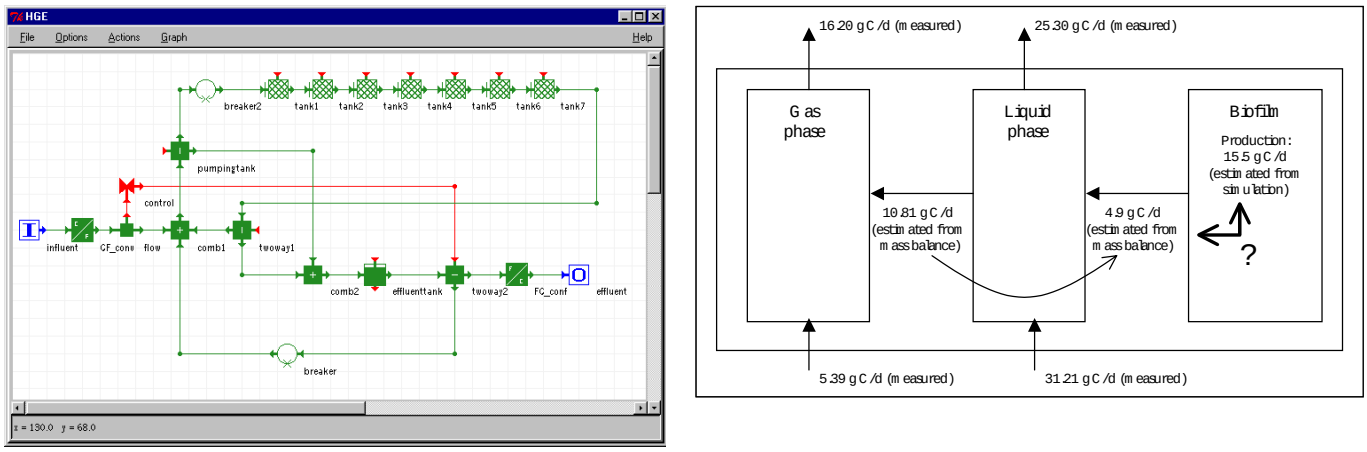

Figure 2 Filter layout in the WEST simulator (Hemmis NV, Kortrijk, Belgium) (left) and carbon balance of the trickling filter system after the load shift (at low loading) (right)

Table 2 Comparison between measured and simulated outflow O_2 and CO_2 concentrations and fluxes after the load shift (at low loading)

Compound	*Measured Concentration*	*C-Flux (g C/d)*	*Simulated Concentration*	*C-Flux (g C/d)*
O_2 gas (vol%)	20.77		20.67	
CO_2 gas (vol%)	0.15	16.20	0.27	29.11
$CO_{2,aq}$ (mol/m^3)	0.22	1.10	0.17	0.85
HCO_3^- (mol/m^3)	4.83	24.20	4.41	22.09

At high loading, however, a quite high discrepancy was seen in the off-gas concentrations (Table 2). The reason for this was sought by calculating a carbon balance (Figure 2). At low loading conditions, the net C-flux removed from the water phase was 5.91 g C/d. The gas phase concentration of CO_2 was increased with 0.1 vol% during the passage through the filter. Using the measured air flow rate of 21.6 m3/d and the ideal gas law at 20ºC, this means a net C-flux of 10.81 g C/d left the filter through the gas phase. Subtracting the 5.91 g C/d that was removed from the water phase from the 10.81 g C/d that entered the gas phase, leaves 4.9 g C/d to be produced by the biomass in the filter. In the simulations however, the net carbon production by the biomass was estimated to be 15.5 g C/d, including the 1.5 g C/d that was consumed by the autotrophic organisms for growth. Obviously, using these measurements, the mass balance of the measurements after the load shift is not correct.

After the data analysis and the model description of the load shift, the possibility of the existence of a leak in the off-gas collection system was investigated. A leak was found which was caused by the installation of a new gas pump in the experimental set-up. The situation was fixed and a new period with

a low influent load to the trickling filter systems was studied. When these new off-gas measurement results were included in the carbon balance computed in Figure 2, it became possible to close the balance. This supports the quality of the conversion rates computed using the simplified mixed culture biofilm model.

Conclusions

A pilot-scale trickling filter was used to investigate the dynamic model description of such a filter's behaviour. Therefore, the filter was subjected to a load shift experiment during a measurement campaign. During this campaign, the COD and nitrogen content of the water phase at different locations in the filter set-up was measured. Also the off-gas composition for oxygen and carbon dioxide was measured. To be able to use the measurements, extra analyses of the inorganic carbon content of the liquid phase were needed as well as measurements of the pH in the filter. A simplified mixed-culture biofilm model was used to model the load shift experiment. This model was extended with a part describing the production and consumption of gaseous components in the filter.

It could be concluded following a drop in the loading of the filter system that the nitrification capacity increased due to a higher availability of oxygen for this process. The start-up of nitrification could be followed using the model. The off-gas analysis measurements supplied extra information to calibrate the gas-liquid mass transfer coefficient. On top of that, the combined interpretation of the carbon dioxide and the inorganic carbon measurements together with the model calculations made it possible to find a leak in the off-gas collection system. After repairing this leak, it became clear that the model predictions were indeed an accurate description of the filter's behaviour.

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