NON-INVASIVE AND CONTINUOUS MONITORING OF A PILOT-SCALE TRICKLING FILTER: WEIGHT, OFF-GAS AND HYDRAULIC CHARACTERIZATION

H. Vanhooren, G. Boeije, F. Accoe and P.A. Vanrolleghem

Department of Applied Mathematics, Biometrics and Process Control (BIOMATH), University of Gent, Coupure Links 653, B-9000 Gent, Belgium

ABSTRACT

A pilot-scale trickling filter has been constructed in order to collect experimental data on a fully characterized biofilm system for the selection, development, calibration and corroboration of mathematical models which describe such a system's dynamic behavior. The design of the unit was made such that it allows a full characterization of the relevant model parameters, and an easy monitoring of the system's performance only using measurements of inflow and outflow. By means of an electronic balance, the weight of the filter unit is continuously monitored. It is shown that information about the filter's weight can be used to accurately determine biofilm and hydraulic characteristics. Also the off-gas is continuously monitored for CO_2 and O_2. These measurements allow to establish closed carbon and oxygen mass balances. Several short term experiments are conducted to reveal the possibilities of off-gas analysis to monitor, model and control the filter's performance.

Two tracer tests were conducted on the filter without and with biofilm. NaCl and Thioflavine-S were used as a tracer. The hydraulic behavior of the filter without biofilm could be described using an advection-dispersion model. If a biofilm was present however, a CSBR (continuously stirred biofilm reactor) approach was found to yield an optimal description of the hydraulics.

KEYWORDS

biofilm modeling, hydraulic characterization, off-gas analysis, simulation, tracer test, trickling filter operation

INTRODUCTION

The growth of microbial species inside attached biological films causes a significant transfer of substrates between the biofilm and the bulk liquid. Considerable effort has been made in the last 25 years to develop adequate mathematical models for the description of substrate utilization and population dynamics in biofilms. The fact that makes such biofilm models relatively complex is that not only the microbial conversion of substrate needs to be considered but also the diffusive transport of substrates inside the biofilm. Recent advances in biofilm research (see among others, Lewandowski *et al*., 1994; Zhang and Bishop, 1994; Bishop, 1997) conclude that also the heterogeneity of the biofilm must be taken into account. However, these highly mechanistic model descriptions inevitably also lead to the use of several empirical relations to describe process dynamics that are not (yet) fully understood. Moreover, their application in practice requires extensive calibration because they contain a considerable number of parameters. Certain fields where biofilm models are used (optimization of design and operation, control, …) however impose a limit to their complexity because the calibration efforts and the calculation intensity have to be feasible.

When searching for an appropriate model complexity for a given objective, the question can be asked - with all the uncertainty in mind - whether it is not equally important to focus on precise description of the advective transport in biofilm systems. Moreover, other processes, like liquid-gas exchange, should be focused upon. Gas phase measurements indeed may provide us with an excellent tool to monitor the performance of a biofilm system in a non-invasive way. Theoretical evaluation (Hellinga *et al.*, 1996) shows us that the OUR (oxygen uptake rate) and the CPR (carbon dioxide production rate) contain a lot of information about the biological processes occurring in the system.

In this paper the construction of a pilot-scale trickling filter is presented in which non-invasive measurement techniques will be studied with respect to their usefulness within a context of calibration of models for process optimization. The techniques evaluated here are off-gas analysis and weight measurements, in addition to continuous fluorescence measurements for hydraulic characterization.

DESIGN OF A LAB SCALE TRICKLING FILTER

The filter unit's dimensions were chosen to represent a cylindrical core taken from a full-scale unit. The depth of the filter column is 1.8 m. The filter surface area A = 0.118 m^2, and the volume V = 0.213 m^3. To allow easy quantification of specific surface area and biofilm parameters, a plastic carrier medium (polypropylene) was chosen. The selected medium has a specific surface area of 220 m^2/m^3. An overview of the filter hydraulics can been seen on Figure 1.

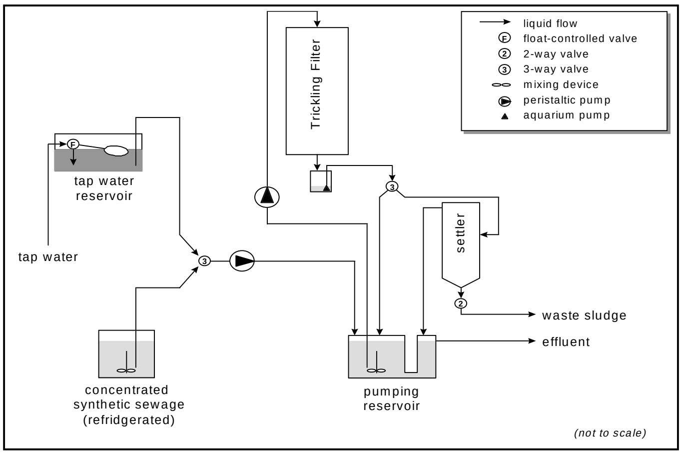

Figure 1. Overview of trickling filter hydraulics

Table 1. Operational parameters of the trickling filter

parameter (unit)	value	st. dev.
biofilm density (g/L)	38.8	0.8
mean biofilm thickness (µm) (based on 7 individual carriers)	470	140

A design volumetric loading rate B_V = 0.6 kg BOD/m^3.d was selected. Nitrification is not expected. The hydraulic surface loading rate B_A was set at 15 m^3/m^2.d (= 0.625 m/h). Based on the hydraulic surface loading rate, the total flow through the filter (influent + recycle flow) can be calculated to be 1.77 m^3/d. Assuming an influent BOD level of 300 mg/L (typical for domestic sewage), the influent flow $Q_{influent}$ can be calculated to be 0.424 m^3/d and the daily BOD flux into the filter is 127.2 g/d. The recycle ratio R is 3.5. An upward air flow through the filter of 7.5 L/min is applied. For reproducibility of the experiments, and to allow easy characterization, it was decided to use a synthetic influent.

TRICKLING FILTER OPERATION

An overview of the operational parameters of the trickling filter after 6 months of rather stable operation can be seen in Table 1.

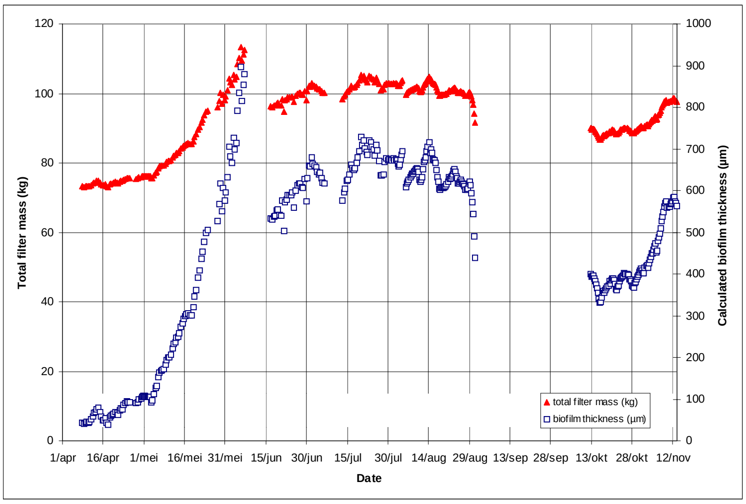

Figure 2. Filter mass and biofilm thickness

A method was devised to continuously monitor the thickness of the biofilm using the electronic balance on which the trickling filter unit is placed (Figure 2). First, the dry mass of the filter, 62.930 kg, was determined prior to the experiments. Several experiments were performed before any biofilm had developed. The total mass of water, 6.66 kg, present in the filter was determined at a filter inflow rate equal to design operating conditions. By means of a 'draw' experiment, the 'wet' mass of the filter could be measured when no influent flow was applied. This way, it was possible to quantify the 'dynamic' and 'static' amount of water present in the filter. Assuming that the 'static' water mass is not affected by the presence of biofilm, the mass of wet biofilm in the filter can be determined form the weight data (Figure 2). During another 'draw' experiment, which was conducted approximately one month after inoculation of the filter, a biofilm mass of 4.97 kg was measured. The wet biofilm mass can be converted to volume by assuming a density of 1 kg/L. If this volume is divided by the total surface area within the filter (46.86 m^2), an average biofilm thickness is obtained. Note that the more biomass develops in the filter, the less important the exact volume of the 'static' water layer becomes.

COD and suspended solids measurements were performed at regular time intervals, the results of these measurements are summarized on Table 2 and Table 3. The variability of the results is rather high. This has to do with irregular sloughing events and thus a highly varying suspended solids concentration. It also proved difficult to keep the COD-concentration of the concentrated influent solution constant. The overall COD-removal efficiency remained however remarkably constant (87 ± 2.2 %) during the whole period of filter operation.

Table 2. Chemical Oxygen Demand

Sampling Location	CODt (mg/L)	CODs (mg/L)
(1) Influent	352 ± 34	284 ± 67
(2) Pumping reservoir	182 ± 69	96 ± 31
(3) Filter outflow	61 ± 24	47 ± 16
(4) Final Effluent	50 ± 20	43 ± 14

Table 3. Suspended Solids

Sampling Location	SS (mg/L)
(1) Influent	124 ± 51
(2) Pumping reservoir	22 ± 14
(3) Filter outflow	33 ± 31
(4) Final Effluent	15 ± 8

HYDRAULIC CHARACTERIZATION

Two tracer tests were conducted on the filter with and without biofilm (i.e. before the startup of the biological experiments). The results of these tests can be seen on Figure 3 (note the difference in time scale). NaCl and Thioflavine-S were used as inert tracer. A fixed amount of tracer was injected into the filter as a pulse. The NaCl was detected in the effluent of the filter using conductivity measurements. Thioflavine-S was detected using continuous fluorescence measurements (Ingold Fluorosensor). During the tracer tests, the filter was operated in 'single-pass' mode (hence, no effluent recycle was applied).

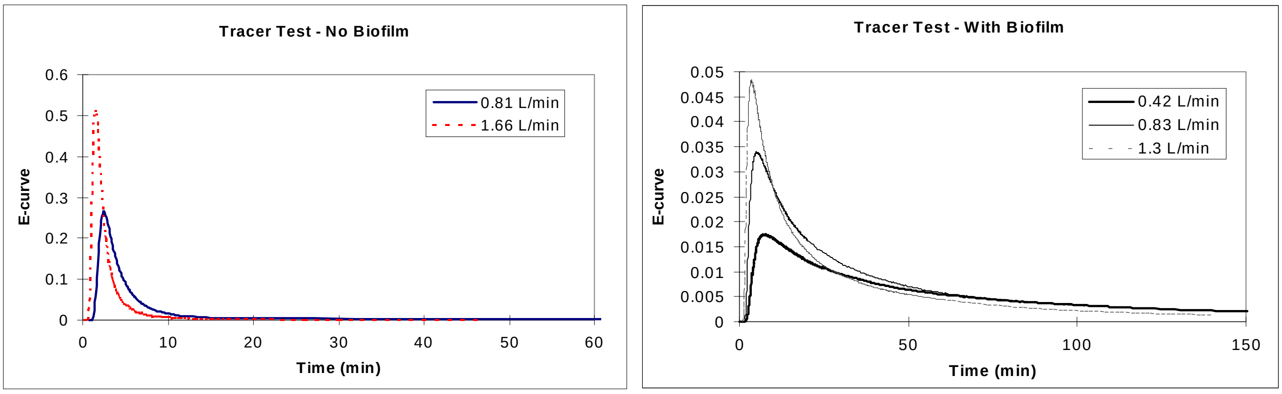

Figure 3. Tracer test results without (left, NaCl) and with (right, Thioflavine S) biofilm

Based on the tracer response curve, the mean hydraulic retention time could be calculated. The experimental results were also fitted to the formula of the advection-dispersion model for a relatively large deviation from plug flow ($D/uL > 0.01$) (Levenspiel, 1972).

$$E_t = \frac{u}{\sqrt{4\pi Dt}} \exp\left[-\frac{(L-ut)^2}{4Dt}\right] \qquad (1)$$

with u the superficial liquid velocity (m/s), D the dispersion coefficient (m^2/s) and L the length of the pipe (m). For the tracer test in the trickling filter, with no biofilm present, the results are given in Table 4.

This best fit was found with the parameter values given in Table 4 (using SPSS software, version 7.5, SPSS Inc.). The correlation R^2 indicates the quality of the fit was acceptable but not perfect. The measured tracer response data were heavier in the right tail region compared to the model. As an example, the fit with the flow rate of 1.66 L/min can be seen on Figure 4.

Table 4. Tracer test - No Biofilm - HRT's and advection-dispersion parameters

	0.81 L/min	1.66 L/min
mean HRT (min)	8.75	3.28
u (m/s)	0.009491	0.017159
D (m^2/s)	0.002533	0.003685
L (m, fixed)	1.8	1.8
R^2	0.89476	0.96286

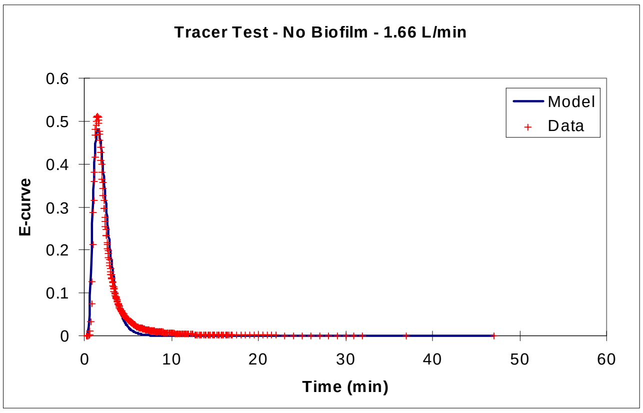

Figure 4. Tracer Test - No Biofilm - 1.66 L/min - Advection-dispersion model

For the tracer test in the trickling filter with biofilm present, the HRT's and advection-dispersion parameters are given in Table 5. Due to the large difference in hydraulic retention time compared to the case without biofilm, it is very likely that diffusion of the tracer in and out of the biofilm has a major influence on the tracer test response curve (Figure 3).

Table 5. Tracer test - With Biofilm - HRT's and advection-dispersion parameters

	0.42 L/min	0.83 L/min	1.3 L/min
Mean HRT (min)	84.0	40.0	38.6
u (m/s)	0.001312	0.002288	0.003207
D (m^2/s)	0.002319	0.003179	0.004682
L (m, fixed)	1.8	1.8	1.8
R^2	0.94287	0.93943	0.91104

Therefore, the tracer test data have also been interpreted using the "Continuously Stirred Biofilm Reactor" approach (Wik and Breitholtz, 1996). Each CSBR consists of a CSTR that is connected to a biofilm compartment by a diffusive link permitting diffusion of the tracer in and out of the biofilm compartment. In such model, parameters available for optimization are (1) the number of tanks, (2) the volume of CSTR's and biofilm compartments and (3) the exchange rate constant. To minimize the number of parameters to be estimated, an exponential function for the volume decrease of the tanks along the depth of the filter was chosen (equation 2).

$$V_i^w = V_\alpha \cdot e^{-i\cdot\alpha} \text{ and } V_i^{biofilm} = V_\beta \cdot e^{-i\cdot\beta} \qquad (2)$$

The best fit (using WEST++ software, Hemmis, Kortrijk) was found with 7 CSBR's in series. As an example, the model fit for a flow rate of 1.3 L/min through the filter - the design flow rate - is given on Figure 5. A correlation (R^2) of 0.997 was found. The parameters found were $V_\alpha = 1.59$, $\alpha = 0.165$, $V_\beta = 84.3$ and $\beta = 1.136$. The modeled retention time of the water, 4.67 minutes, is the main stream CSTR's (with a total volume of 6.07 L) was found to be in close agreement with the residence timed found in the no-biofilm case.

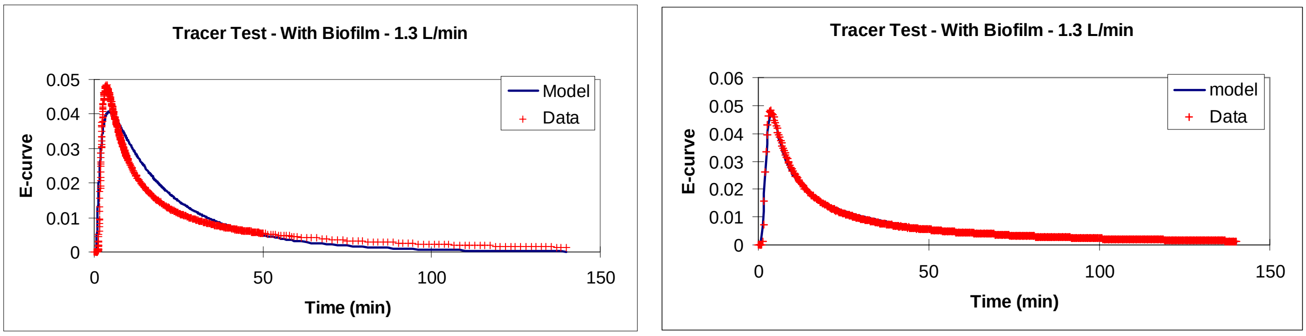

Figure 5. Tracer Test - With Biofilm - 1.3 L/min – Advection-dispersion model (left), CSBR model (right)

OFF-GAS MEASUREMENTS

Several short term experiments were conducted to reveal the possibilities of off-gas analysis. The measurement instrument was a Maihak Multor 610 gas analyser. Calibration of the instrument is only needed every two days. Off gasses are taken from the top of the filter. The time for the gas to be transported from the filter to the analyser is 20 seconds. The time constants of the sensors are 20 seconds for the O_2 and about 40 seconds for the CO_2 analyser.

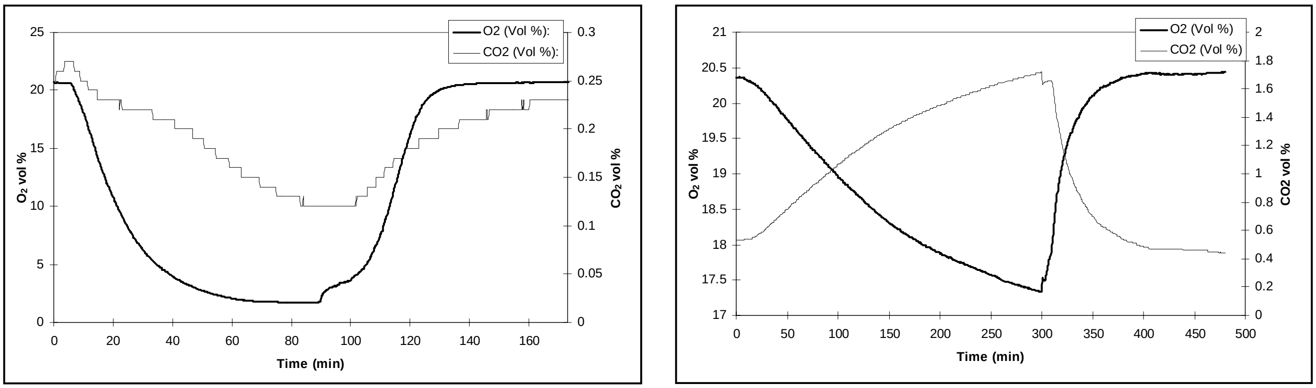

Figure 6. Results of the change aeration of the gas composition from ambient air to N_2 (left), and from the change in aeration flow rate from 7.5 L/min to 0.45 L/min (right)

The experiments included (i) step changes in the superficial velocity of air through the filter - from 3.8 m/h down to 0.23 m/h - (ii) a step change in the composition of the gas used for aeration - pure nitrogen gas instead of ambient air - and (iii) a step change in the influent concentration. The results of the first two test is shown on Figure 6.

A lag phase of about 5 minutes can be seen at the beginning of the tests after which a clear response from the system on the applied steps changes can be seen. In the second experiment, we observe that the gas phase is gradually depleted for oxygen and accumulated increasing amounts of CO_2. The gas phase is very close to be stagnant.

The result of the influent concentration step change from normal influent to tap water can be seen on Figure 7. During the first 20 hours of the test, the concentration change of both O_2 and CO_2 looks normal, with a decrease of CO_2 and an increase of O_2 due to lowered oxidation rates. However, after this period, a sudden decrease of the O_2 concentration can be observed without concomitant increase in CO_2 evolution. Under normal operating conditions, no significant nitrification is expected. There is however some autotrophic biomass present in the filter leading to a small nitrification activity. During the test, more oxygen becomes available for nitrification. As a result, the autotrophic biomass can start to nitrify more intensively. This hypothesis was checked using the nitrogen and COD measurements. Also an unexpected change of the measured RQ (respiration coefficient) in Figure 7 points in this direction. The RQ is the ratio between CO_2 production and oxygen consumption, and is near 1 for heterotrophic growth (Hellinga *et al.*, 1996). It will drop in case significant nitrification occurs.

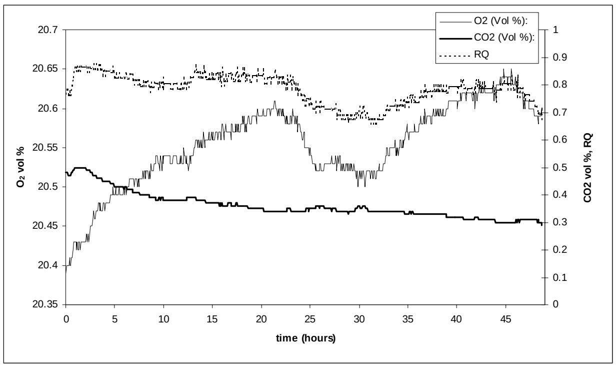

Figure 7. Results of the step change in influent concentration

CONCLUSIONS AND FUTURE APPLICATIONS

Both the tracer tests and the off-gas measurements have applications in modeling, optimization and control of biofilm systems. Using tracer tests makes is possible to select appropriate models for the description of the hydraulics in biofilm systems. Theoretical studies as well as the short term tests conducted in this study reveal some of the possibilities of off-gas analysis as a tool for modeling and operation of biofilm systems. Weight measurements have been shown to be particularly useful for such pilot-scale studies as they allow continuous biofilm thickness monitoring. The next steps in this research will be to conduct extra short and long term experiments focusing on the characterization of the bioconversions. A completely closed carbon balance can be obtained with measurements of the carbon content in the liquid phase entering and exiting the reactor. The results of these test will then be summarized using the biofilm model recently developed by Rauch *et al.* (1999) adapted for off-gas measurements by adding mass balances and inorganic carbon equilibria.

ACKNOWLEDGEMENT

Financial support for this work was provided by the Fund for Scientific Research - Flanders (Belgium) (F.W.O.). The first author is Research Assistant of the Fund for Scientific Research - Flanders (Belgium).

REFERENCES

Bishop P. (1997). Biofilm structure and kinetics. *Wat. Sci. Tech.*, **36**(1), 287-294.

Hellinga C., Vanrolleghem P., van Loosdrecht M.C.M. and Heijnen J.J. (1996). The potentials of off-gass analyses for monitoring waste water treatment plants. *Wat. Sci. Tech.*, **33**(1), 13-23.

Levenspiel O. (1972). *Chemical reactor engineering*. 2th edit., New York, Wiley.

Lewandowski Z., Stoodley P., Altobelli S. and Fukushima E. (1994). Hydrodynamics and kinetics in biofilm systems - recent advances and new problems. *Wat. Sci. Tech.*, **29**(10-11), 223-229.

Rauch W., Vanhooren H. and Vanrolleghem P. (1999). A simplified mixed-culture biofilm model. *Wat. Res.*, accepted for publication.

Wik T. and Breitholz C. (1996). Steady state solution of a two-species biofilm problem. *Biotechnol. Bioeng.*, **50**, 675-686.

Zhang T.C. and Bishop P.L. (1994). Density, porosity and pore structure of biofilms. *Wat. Res.*, **28**, 2267-2277.