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MODELLING FOR OPTIMISATION OF BIOFILM WASTEWATER TREATMENT PROCESSES: A COMPLEXITY COMPROMISE

MODELBOUW VOOR OPTIMALISATIE VAN BIOFILM-WATERZUIVERINGSPROCESSEN: EEN COMPLEXITEITSCOMPROMIS

door

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Summary

In the literature review in chapter 2 of this thesis, it became clear that a whole range of biofilm models is available, ranging from relatively simple one-dimensional models to comprehensive 3D descriptions of the biofilm structure evolving in time and space. Each of these models has its value and its possible applications. The complexity of the model that is selected should however be relevant for the application it is used for. High complexity models clearly have the advantage of including a lot of the available knowledge about biofilm processes. However, they are too detailed for use in full-scale on-line applications. On the other hand, low complexity models are not able to describe all the dynamics of the system, since they are simplified.

In this thesis, a model was developed and applied that attempts to be a complexity compromise. The main advantage of the model is the avoidance of the numerical solution of partial differential equations. This was obtained by decoupling the calculation of substrate diffusion into the biofilm from the computation of the conversion processes in the biofilm by using a two-step procedure that resulted in a fairly simple model structure. This aspect makes the proposed model an attractive alternative to the existing complex models when emphasis is put more on fast predictions of system behaviour than on detailed understanding. Furthermore, it makes it more suitable for applications that combine it with widely accepted models for other wastewater treatment unit processes. Despite its relatively simple structure, the model is still able to calculate the conversion rates of processes in the biofilm performed by different biomass species. It can thus be used to describe processes occurring at different depths of the biofilm.

In addition to the original model, two extended model descriptions were developed. In the original model, an instantaneous steady-state profile for soluble substrates in the biofilm is used and soluble components emerging from conversion processes inside the film are assumed to be subject of immediate out-diffusion at the surface of the biofilm. Together, these assumptions are in principle violating the mass balances during dynamic simulation. The first extension of the model accounts for the possible accumulation of soluble components in the biofilm and it therefore guarantees a correct determination of the penetration depths. In the second extension, the introduction of an external diffusional resistance was studied. Although considered not important in biofilm systems with a relatively turbulent liquid phase, it should be included in some cases where this resistance may be of big importance for the correctness of the model predictions.

In order to successfully use the developed models in applications for process optimisation, the simulation tool WEST (Hemmis NV, Kortrijk, Belgium) was optimised and used. One of the key features of WEST is its possibility to integrate multiple processes. For example, in this work, WEST was used to study treatment systems where conversion processes are simultaneously taking place in a biofilm and in the liquid phase. To enable this coupling, a powerful model base structure was developed. This model base is aimed at maximal re-use of existing knowledge and is therefore structured hierarchically. Thanks to this structure, new models can be implemented using the compact matrix format (Petersen, 1965) selected by the IWA task group on mathematical modelling (Henze *et al.*, 1987).

In order to test the simplified mixed-culture biofilm model, a pilot-scale trickling filter was designed and built. The filter was constructed to allow the collection of experimental data on a fully characterised biofilm system. Non-invasive on-line monitoring of the filter was possible by means of an electronic balance and off-gas analysis measurement equipment that continuously monitored the off-gas of the filter for CO_2 and O_2. To

characterise the filter's hydrodynamic behaviour, two tracer tests were conducted in the absence and, later on, in the presence of biofilm. If a biofilm was present a CSBR (continuously stirred biofilm reactor) approach (Wik and Breitholtz, 1996) was found necessary to yield an adequate description of the hydraulics. For a good description of the pilot-scale filter, 7 CSBR's in series were needed.

This pilot-scale filter was first subjected to a pollutant load shift. During this experiment, it could be concluded that, following a drop in the loading of the filter system, the nitrification capacity increased due to a higher availability of oxygen for this process. The simplified mixed-culture biofilm model introduced in this thesis was used to model the load shift. To be able to use the off-gas measurement results in the model calibration, this model was further extended with a submodel for the description of the production and gas-liquid exchange of carbon dioxide. This submodel was based on the model developed by Spérandio and Paul (1997). The extended biofilm model was subsequently integrated in the CSBR model. The start-up of nitrification could be followed using the model, provided the decay coefficient for autotrophic biomass was sufficiently low to assure a certain amount of autotrophs to stay in the system during the high loading period.

In a second test, it was attempted to induce denitrification at high organic loading rates by adding nitrate. This test showed that denitrification could be induced and that this way a considerably increased substrate removal capacity could be obtained. During the addition of nitrate, the production of CO_2 from bioconversion processes increased, while no decrease of the O_2 consumption was noticed. For the modelling of this experiment, the model calibrated to describe the load shift was used. The model performed very well and furthermore it was possible to obtain a value for the effective diffusion constant of readily biodegradable substrate in the biofilm.

A second series of model applications was performed at an industrial wastewater treatment plant. More specifically, the performance in COD removal and the stripping of volatile organic compounds (VOC's) of the trickling filters were studied. To this end, the process characteristics of the filters were quantified by means of a 5-day intensive measurement campaign with the use of an on-line respirometer complemented with on-line off-gas analysis.

The model was calibrated and could follow the measured effluent and off-gas concentrations very closely. In contrast to what was initially expected, the O_2 and CO_2 measurements revealed that the system was not always oxygen limited. In the model calibration the use of a very low value of the diffusion constant for readily biodegradable substrate was found to be the best means for describing the observed data. As only a very limited amount of phosphate was available in the influent, the effect of the dosing of phosphate on the trickling filter system was studied too. It could be noticed that the net phosphate uptake by the biofilm was very limited under normal operating conditions, since the added phosphate dosing did not bring along better treatment efficiency. However, shortly after the start of the dosing, a clear effect on the off-gas measurement results and the sludge production was seen. This effect damped out in some days time and could only be modelled by temporarily increasing the yield coefficient for heterotrophic growth, making the oxygen consumption to decrease and the sludge production to increase.

Next to high COD and nitrogen concentrations, a considerable part of the chemicals in the industrial wastewater was highly volatile. Therefore, the VOC removal in the industrial wastewater treatment plant was monitored and modelled. The capital and operating cost and the efficiency of a new off-gas treatment facility are dependent on the air flow to be treated and the concentration of VOC's. Two mathematical models describing the stripping of VOC's were developed. The first model was a model for the fate of individual chemicals that was built on the basis of the *SimpleBox* approach (van der Meent, 1993) combined with the existing steady-state biofilm diffusion/biodegradation model of Melcer *et al.* (1995). The second model was a simple dynamic model that was built on the basis of the results obtained with the steady-state model. These results showed that biodegradation and adsorption to suspended solids could be neglected for the volatile organics under study and that the model could further be simplified to a simple mass balance model for the gas-liquid exchange of the VOC's. Scenario analysis with the dynamic model showed that stripping was virtually independent of the applied air flow rate. The simulations, however, revealed that immediately after changes in air flow rate, quite high flux and concentration peaks were to be expected. Using the findings of this research, the air flow rate and the air flow pattern through the wastewater treatment plant were changed so as to obtain a lower overall air flow combined with a relatively constant VOC concentration. This way, the investment costs for the off-gas treatment facility could be substantially lowered.

As a last part of this thesis, suspended-carrier biofilm systems were studied. Qualitative steady-state analysis of these systems already showed its interesting features (Yuan *et al.*, 2001). In this thesis, these features were validated quantitatively based on a simulation benchmark for activated sludge treatment systems (Spanjers *et al.*, 1998; Copp, 2001). This simulation benchmark had to be extended with the biofilm model introduced before. The Activated Sludge Model No 1 (Henze *et al.*, 1987) had to be coupled to the simplified mixed-culture biofilm model. It should be noted that no simulation studies were found in literature describing the simultaneous degradation of organic matter in a biofilm and in the liquid phase by activated sludge flocs. This study can therefore be considered as the first application of such integrated modelling and simulation approach. Two types of attached growth processes were studied. In the first, carriers were only added to the aerobic zone of the plant in order to enhance nitrification in a relatively small volume and at low sludge retention times. It was noticed that the longer retention time of the biomass growing on the carriers stimulates nitrification. However, a rather strong dependency of the performance on the dissolved oxygen concentration was obvious, causing the required aeration energy to increase significantly. Moreover, the overall effluent quality that was achieved was worse than that of the benchmark plant.

The second plant layout studied included the addition of carriers to all zones of the plant. The simulation results again showed that the retention times of heterotrophs and autotrophs are different and that autotrophs are mainly present in the zones of the plant where they are needed. Also, the leakage of readily biodegradable material from the anoxic zone to the aerobic zone of the plant was limited. This entails that full nitrogen removal can be accomplished at lower C/N ratios in the influent. However, it was found that this plant layout is even more sensitive to the dissolved oxygen concentration in the aerobic zone. Therefore, in practical applications, the oxygen control needs to be rather stringent and enough blower capacity should be available to preserve a sufficiently high oxygen concentration at high loading rates.

The above applications of a relatively simple mixed-culture biofilm model and a mass balance model for the gas-liquid exchange of volatile organics show that it is not always needed or even desired to used a complex model in order to obtain valuable simulation results. It can be concluded that, whenever using models for process optimisation, a compromise should be sought between the complexity needed to describe the dynamics of the process, the data available for calibration and the application the model is used for.