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MODELLING STRIPPING OF VOLATILE ORGANICS IN AN INDUSTRIAL TRICKLING FILTER SYSTEM

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ABSTRACT
A model describing the stripping of volatile organic contaminants (VOCs) in an industrial trickling filter system is developed. The aim of the model is to investigate the effect of different operating conditions (VOC loads and air flow rates) on the efficiency of the VOC stripping and the concentrations in the gas and the liquid phase. The modelling is structured in three parts. First, a hydrodynamic model of the liquid phase in the trickling filters is developed using a tracer test with lithium. Next the gas mixing in the filters is studied using continuous CO_2 and O_2 measurements. Both are linked using a liquid-side mass transfer model for VOC stripping. After the model calibration, simulations reveal that changing the air flow rate in the trickling filter system has little effect on the VOC stripping efficiency at steady state. However, immediately after an air flow rate change, quite high flux and concentration peaks of VOCs can be expected. These phenomena are of major importance for the design of an off-gas treatment facility.

KEYWORDS
mathematical modelling, off-gas treatment, stripping, trickling filter, volatile organic contaminants

INTRODUCTION
Industrial wastewater treatment plants often have to cope with highly loaded wastewaters. In many cases, a considerable part of the chemicals in the wastewater is volatile (e.g. solvents). In aerobic biological treatment, these volatile organic contaminants (VOCs) can be stripped out of the water together with the air used for aeration (Melcer *et al.*, 1994). The environmental impact of VOCs is high because some of them are toxic, while others contribute to ground-level ozone generation. In trickling filter systems, stripping is likely to be the most important removal mechanism of volatile components, as VOC biodegradation is known to be low in systems with short retention times (Dobbs *et al.*, 1989; Hsueh *et al.*, 1991).

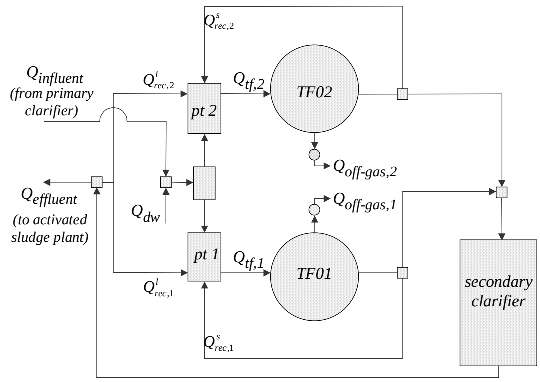

Figure 1: Hydraulic lay-out of the trickling filter system under study (pt = pumping tank, dw = dilution water)

In this study, the VOC removal in an industrial wastewater treatment plant was monitored and modelled. The plant consisted of a downflow trickling filter system with forced countercurrent aeration (Figure 1). Environmental legislation enforces the construction of an off-gas treatment facility. The capital and operating cost and the efficiency of this facility are dependent on the air flow to be treated and the concentration of VOCs.

MODELLING
The modelling of the VOC stripping in this fixed film system was done in three consecutive steps. First of all, the hydraulic behaviour of the trickling filter was modelled using the results of a tracer test. Next, continuous O_2 and CO_2 measurements were used to establish a description of the gas mixing in the filters. Finally, a connection between the liquid and the gas phase was made using a liquid-side mass transfer model (De heyder *et al., 1997*; Melcer *et al.*, 1994).

Hydrodynamics of the trickling filters

The tracer, 5 kg of LiCl, was injected as a pulse in the pumping tank (De Clercq *et al.*, 1999). It was found that the free flowing liquid in the trickling filter could be described as a two tanks-in-series system with two tanks *a* and *b* of 15 m^3 each.

Gas mixing in the trickling filters

To investigate the gas mixing in the trickling filter system, the ventilators were switched from “high” to “low” position. CO_2 and O_2 concentrations were monitored. The system response provided information about the mixing properties of the gas phase inside the reactor. The results show that the gas phase could be modelled as a single perfectly mixed tank of 2000 m^3 (Figure 2). The measured values of the air flow rate were implemented, together with a fixed production rate of CO_2 and a fixed consumption rate of O_2. As will be shown in the next paragraph, this assumptions could be made because the wastewater composition did not change significantly during the short period around the step change in air flow rate and because the biodegradation was not affected by the air flow rate change.

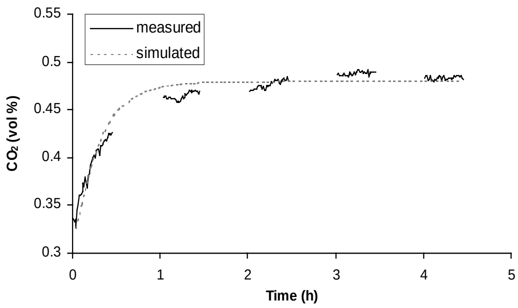

Figure 2: Comparison between simulated and measured CO_2-concentration in the off-gas of TF02 after lowering the air flow rate at time 0

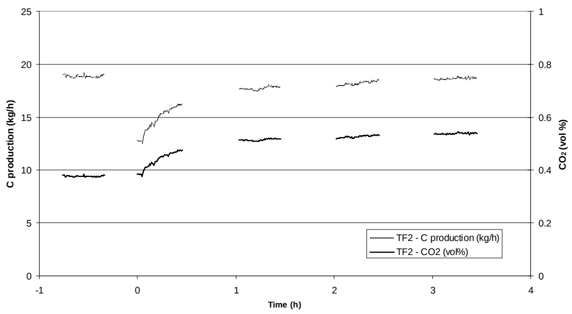

Figure 3: Influence of the air flow change on the C production and CO_2 concentration of TF02

Liquid-side mass transfer model

Once the hydrodynamics of both the liquid and the gas phase were modelled, the coupling between both could be studied. First the assumption made while interpreting the CO_2 and O_2 data had to be verified. As an example, the CO_2 measurements are taken. Shortly after time 0 on Figure 3, the air flow rate through the filters was lowered. After some hours, the total amount of carbon leaving the system via the gas phase returned to the same value as compared to the period before the change. The drop of the C production after the air flow change is due to the transient behaviour of the CO_2 concentration in the gas phase before reaching a new steady state. As no accumulation of inorganic carbon in the liquid was noticed during the measurements, the microbially produced CO_2 was constant. The change of air flow and air retention time apparently has no effect on the oxygen and carbon dioxide mass transfer to and from the water and the biofilm.

Six measurements for VOCs in the liquid and the gas phase of filter TF02 were done before the change of the air flow rate, four measurements were done after that. The results were averaged to minimise the effect of measurement errors. The VOC loading was quite different before compared to after the air flow change. After the lowering of the air flow rate, the load (influent flow as well as influent concentration) increased considerably. Mass balances for VOCs showed that biodegradation of the most volatile components could be excluded from the model. Basically, the model consisted of a coupling between the hydrodynamic models developed above. The flux from liquid to gas phase was modelled as follows (for both tanks a and b):

$$N_{s,a/b} = K_L a \cdot \left(C_{liquid,a/b} - \frac{C_{off-gas}}{H_{VOC}} \right) \quad (1)$$

The model was calibrated using the two data sets available (Figure 4). Values for the Henry coefficients H_{VOC} were obtained from Sander (1996). The only parameter yet to be determined was the K_La for the different VOCs. The VOCs treated here are very volatile and have a relatively low water-solubility. According to the two-resistance theory (Treybal, 1980), the gas-side mass transfer resistance can be neglected in this case. The liquid-side mass transfer resistance is closely related to the components' water diffusion coefficient. Water diffusion coefficients of low water soluble components however are difficult to measure and therefore very rarely stated in literature. Only approximations using formulas are found in literature (e.g. Perry and Chilton, 1974). With these uncertainties in mind, it was decided to use the same mass transfer coefficient for all highly volatile components under study.

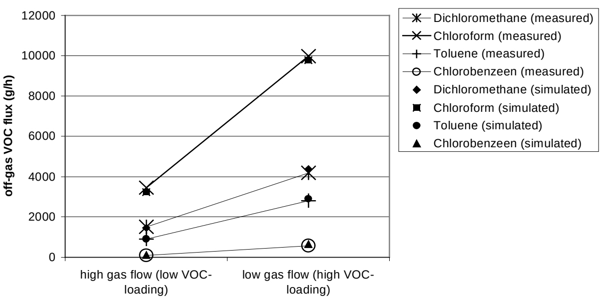

Figure 4: Result of the calibration of the VOC flux in the off-gas of TF02 with a fixed K_La of 50 h^{-1}

SCENARIO ANALYSIS

After model reduction and calibration, simulations were done to predict the effect of a third situation, namely a high loading of VOCs in the influent together with a high air flow rate. This situation was compared with the high loading – low air flow case. The question to be answered was whether the stripping efficiency would be higher with a high flow. Some simulation results are shown on Figure 5. A small increase of the VOC flux and the stripping efficiency was noticed. A high air flow rate resulted in a larger driving force for stripping because of the higher concentration gradient at the gas-liquid interface. On the other hand, a high flow rate also means a lower gas residence time. The combination of these two effects diminished the effect to only a few percentages in removal efficiency and slightly lower effluent concentrations at the high flow rate. The air flow rate can thus be lowered without incurring a considerable effect on the stripping efficiency, but it will obviously result in higher concentrations in the air to be treated by the off-gas treatment facility.

At the industrial wastewater treatment plant under study, an overall waste gas management strategy is to be implemented over the next year. Waste gasses are coming from the equalisation system, the trickling filters and the sludge treatment. The waste gas flow rate coming from the sludge treatment (filter presses) is not constant because of batch-wise ventilation during day-time. Four times a day, the presses have to be opened during 30 minutes for cleaning. During these periods, the air flow coming from the presses hall increases from 2.200 m^3/h to 7.600 m^3/h. To keep the flow rate in the off-gas treatment facility constant, the flow over the two trickling filters could be temporarily lowered during these periods. It is therefore important to know what effect these gas flow rate changes will have on the concentration and the total load of the VOCs in the off-gas treatment facility.

Dynamic simulations were performed to predict the flux and concentration profiles immediately after an air flow change. The results of these simulations are shown in Figure 6. As an example, only chloroform is shown. At time 0, the air flow through the filters is decreased during 30 minutes to allow the waste gas treatment to cope with the high air flow coming from the sludge treatment. In this period, the concentration in the trickling filters off-gas increases as seen above. The increase of the flow rate after this 30 minutes period, therefore results in a quite high flux-peak of chloroform to the VOC treatment facility. The chloroform concentration in the trickling filter off-gas immediately starts to drop during high flow periods. These are factors certainly to be taken care of when designing the off-gas treatment facility.

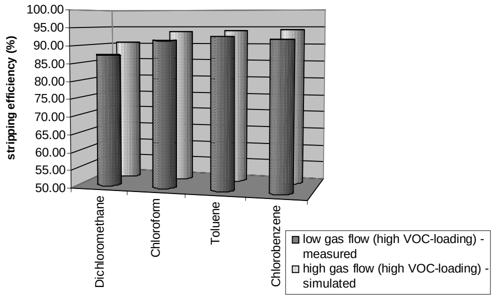

Figure 5: Effect of two different air flow rates on the VOC removal efficiency in the off-gas at high VOC loading

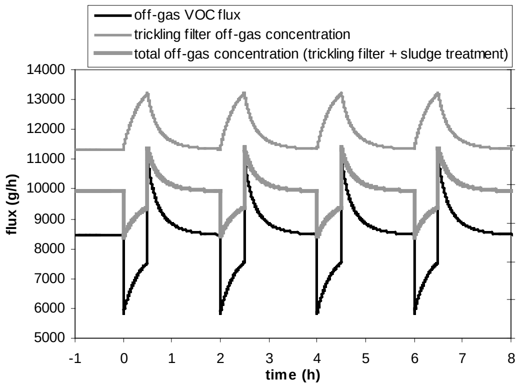

Figure 6: Effect of an air flow change (low to high air flow) with a constant wastewater composition on the flux and the off-gas concentration of chloroform at the trickling filters and the VOC treatment facility

CONCLUSIONS

A mathematical model describing the stripping of VOCs in an industrial wastewater treatment plant was developed. The hydrodynamics of the trickling filters could adequately be described with a tanks-in-series model. Calibration of this model was done using the results of a tracer test with lithium. The gas mixing inside the filter could be described by a single perfectly mixed tank with the actual gas volume of the reactor. The validity of this description was proven by continuous CO_2 and O_2 measurements in the gas phase of the filters. The air flow rate did not affect the biodegradation capacity of the trickling filter system. Liquid and gas phase mixing models were linked using a mass transfer model for the stripping of VOCs. This model was calibrated using a single mass transfer coefficient for all VOCs under study. Stripping showed to be virtually independent of the applied air flow rate. At high air flow, the total stripping efficiency only increased with a few percentages, resulting in a lower gas phase VOC concentration. Dynamic simulations, however, revealed that immediately after the changes in air flow rate, quite high flux and concentration peaks are to be expected. This should be considered when designing an off-gas treatment facility.

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