Aeration control for simultaneous nitrification-denitrification in a biological aerated filter using internal model approach

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Abstract Experience has shown that simultaneous nitrification/denitrification in a biological aerated filter is possible. However these systems react very sensitively to the aeration control strategies applied. Poorly adapted control strategies induce a strong decrease in treatment efficiency. A new control strategy for simultaneous N/DN is developed. The strategy proposed makes use of ammonia measurements and the inlet and outlet: a Feedback/Feedforward block. Passing by a calculation of the load to be eliminated, an estimation of the air flow velocity to be applied is carried out dynamically. A retroactive loop corrects this prediction in order to reach exactly the desired set point. This control approach has been implemented and tested at pilot plant scale for a period of 18 months. The pilot plant consists of two coupled BAF cells, reflecting closely industrial scale situations. Comparative studies reveal clearly the improved performance of the developed FF/FB control strategy compared to classical controllers. The benefits include 5% increase in nitrogen removal performance and a reduction of 15 to 20% in air requirement, offering a rapid return of investment costs.

Keywords Aeration; BAF; predictive control; simultaneous nitrification denitrification

Introduction

The Biostyr® process, the biological aerated filter (BAF) system of Veoila Water Systems, is a well established process with numerous references in wastewater treatment. For the purpose of nitrification and denitrification (N/DN) traditionally the "classical" configuration of two distinct zones for each reaction is employed. The application of simultaneous N/DN reflects one recent evolution of this process representing an economic optimisation with respect to operation and construction. A reduction of up to 50% with respect to the quantity of air injected can be achieved (Puznava *et al.*, 1999). However, without appropriate control and instrumentation, the control of the air flow rate for good and stable process performance remains difficult (Puznava *et al.*, 2000). This is closely linked to the non-linearity of the biological system and to the fact that the overall system is characterised by an important time delay. These drawbacks can provoke conditions of over- or under aeration leading to a decrease of the overall performance, due to favouring one of the basic reactions (nitrification or denitrification respectively). It is evident that under these circumstances the advantages of simultaneous N/DN will diminish to a certain extent. Consequently there is a need for a more appropriate control strategy ensuring optimal operation of the simultaneous N/DN in BAF systems.

The objective of this paper is to present the new control algorithm ensuring a more effective and precise control. Implemented control laws and relationships are illustrated and the validated control strategy is compared to other control alternatives for the same system.

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Within that frame a brief overview on various existing control strategies is presented below. Payraudeau and Gisclon (1997) present an approach, using the calculated oxygen transfer efficiency (OTE) to control the air flow rate, which involves the dissolved oxygen concentration (DO) as a measured variable. This technique requires the utilisation of a reference OTE, which, however, is dependent on the pollution to be treated (Charpentier and Martin, 1996). Difficulties may arise due to the fact that the pollution load varies in time, which implies a frequent adaptation of the value for the reference OTE.

Other authors, e.g. Nielsen (1993) make use of linear combinations of the state variables (i.e. ammonium and nitrate) in order to calculate the set-point for the air flow rate. Approaches of this type rely on empirical or semi-empirical models and the control functions are mainly based on data, originating from experience of previous operation. The deterioration of the model, due to an evolution of the biomass or of the performance of the filter, represents the major risk of these approaches, as it calls for a frequent correction of the control rules.

Other techniques (e.g. Samuelson and Carlsson 2002; Suescun *et al.*, 2001) rely rather on the control of the aerated volume than the air flow rate, applying, hence, a compartmentation of the reactor. However, the extreme discrete character (discontinuous variation of the aerated volume) of these of strategies, forces the authors always to complete their system with a DO control. Moreover this strategy is applicable to active sludge systems but not really to BAF.

For the cases where the effluent is highly variable, the implementation of the applied load within the control approach is fundamental as the delays between observation and feedback induce often instability of the system. Feedback/Feedforward control loops have been the subject of several publications. As an example, the authors Ingildsen *et al.* (2002) or Carlsson and Rehnström (2002) propose control strategies that address the DO concentration in the biological reactor by using inlet ammonia measurement. Others (e.g. Krause *et al.*, 2002) apply rather the concept of ammonia load in order to predict the set-point for the DO. In general it can be stated that the pollutant load has been accepted as a useful parameter for control purposes, whether as a direct or indirect measure. Indirect measures include the estimation of the corresponding load based on conductivity and turbidity as presented by Audic *et al.* (2001). However, for control systems that need an elevated degree of precision, the use of direct measurements of the pollution is preferred, when possible.

The algorithm presented in this paper aims at a more efficient and precise control. As a consequence the determination of the applied load is based on direct measurements and serves as an inlet to a mathematical model, predicting the air requirement. In addition the algorithm includes a routine, which automatically compensates for changes of the biological performance, i.e. it provides the possibility for permanent correction of the set-point issued. The air flow rate requirement is estimated directly without relying on the DO measurements. The algorithm, detailed below, has been proven to limit over- or under aeration related to peak loads and has been validated on pilot plant bases for a period of 18 months. Recent full scale implementations emphasize the results presented below (Letallec *et al.*, 2005).

Methods

Pilot plant

The pilot plant consists of two identical reactor columns, 30 cm in diameter and 5 m in height (Figure 1). Support material for the biomass is made of uniform polystyrene beads. The wastewater treated is that of the city of Maisons-Laffitte after passing a

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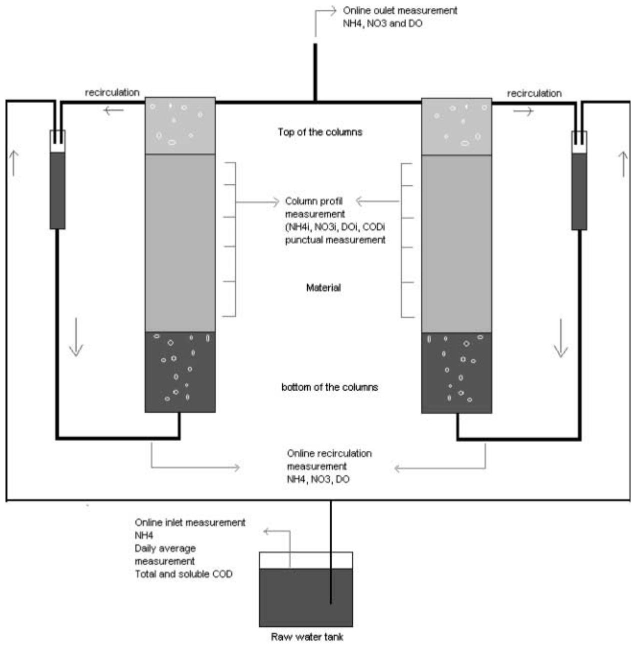

Figure 1 Scheme of the pilot plant

primary settler. The columns are constructed for flexible operation, i.e. for classical N/DN or simultaneous N/DN respectively. This includes for each column an internal recirculation line, which rejoins the according feed line. A supervision /SCADA system integrates the data acquisition and the control routines as well as the command lines for the feed, recirculation and air flow rate.

The two reactor columns are combined in such a way that the overall system resembles a treatment site with two filters/BAF cells. This set up is advantageous for the evaluation of any operational or control strategies, as it reflects more closely the conditions at full scale plants, which always consist of several BAF cells.

The outlet of each reactor columns is hence sent to an intermediate tank (10 L), from which the samples are drawn for the according off – and on-line measurements. In a similar way the feed of the two columns is realised, with a feed pump for each reactor.

Continuous monitoring includes the airflow rate and dissolved oxygen, temperature, NH_4-N, NO_3-N (WTW Trescon units OA110 and ON210) at the inlet and outlet. Daily average measurements included COD, suspended solids, alkalinity and NH_4-N and NO_3-N. The applied loading is calculated for the total amount of support material and varied between 0.3 and 0.6 kg NH_4-N/d/m^3 for the corresponding trial period. The coefficient for the peak flow, i.e. the ratio between the maximum load and the average load during one day remained between 1.8 and 2.5 with an average of 2.3.

Description of the open loop control law

The objective of the control law is to relate the applied NH_4-N load to the air flow rate and air flow velocity (air flow rate divided by the filter surface). The NH_4-N load to take into account is the load really applied to the reactor columns, i.e. it is determined based on the mixture of the settled wastewater with the recirculation water from the outlet. The choice of the real applied load as a variable includes several benefits. It permits us to take simultaneously into account the variation in flow and concentrations. Furthermore it represents a design parameter for full scale applications.

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For certain conditions (NH_4-N concentration not limiting), it can be observed on a daily basis is that the real eliminated load is constant for a given air flow rate and is independent of the applied load. This hypothesis has been validated by a series of tests, where the concentration of NH_4-N and the feed flow rate were varied in such a way that the resulting applied load stayed constant. The airflow rate was also held constant.

Figure 2 illustrates one of these tests. The first vertical dotted red line indicates the moment where the conditions were changed as mentioned above. The green line corresponds to the eliminated load and hence to the response of the system. The peak right after employing the new conditions represents the transient period, i.e. the duration corresponding to the hydraulic residence time of the system (it ends at the second dotted line). It can be observed that, after the transient period, the eliminated load returns its initial level.

A linear relationship can be established between the eliminated NH_4-N load (Cv_e) and the air flow velocity at steady state conditions (equation 1). This relationship, however, does not yet account for transient conditions.

Relationship between eliminated load and air flow velocity

$$V_{air}(t) = \alpha \cdot Cv_e(t) + \beta \tag{1}$$

One of the particularities of the developed algorithm lies within the capability to take into account transient phenomena. For this, first, the eliminated load is calculated via the difference between real applied load and the residual load at the outlet to which a delay, T_g, is applied. This delay corresponds to the average hydraulic retention time in the reactor.

Now the air flow velocity at time t can be expressed as a function of the eliminated load calculated for the same time instant (see Figure 3, *F(t)*). However, this method doesn't take into account the delay between sampling/analysing and effluent arrival in Biostyr material where ammonia starts to be degraded. Also air flow rate variations during the retention time are not included in the calculation. The sum of these phenomena induces a dispersion of the values as illustrated in Figure 3 and hence also an uncertainty of around $\pm 15\%$ concerning value of the air flow rate to be applied. Applying a

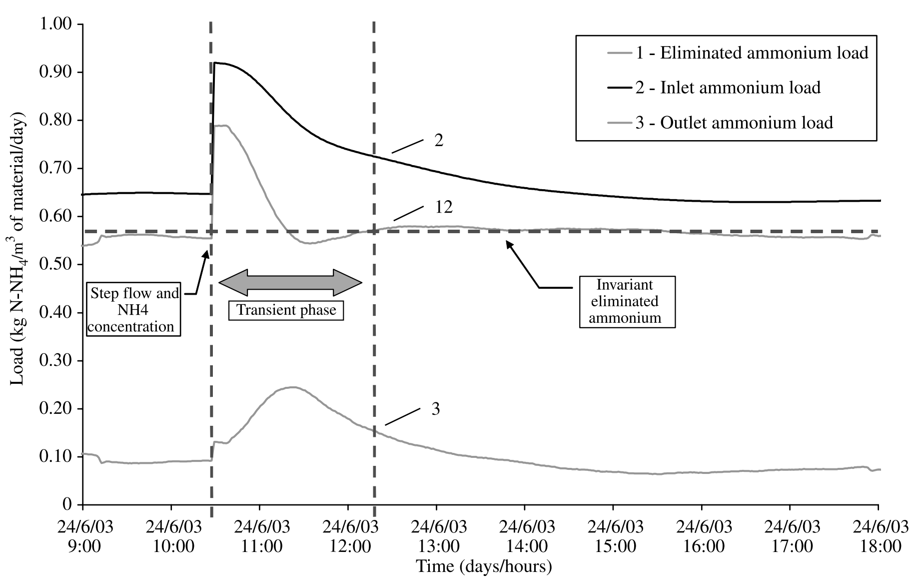

Figure 2 Results: Variation of NH_4-N conc. and feed flow rate at constant load

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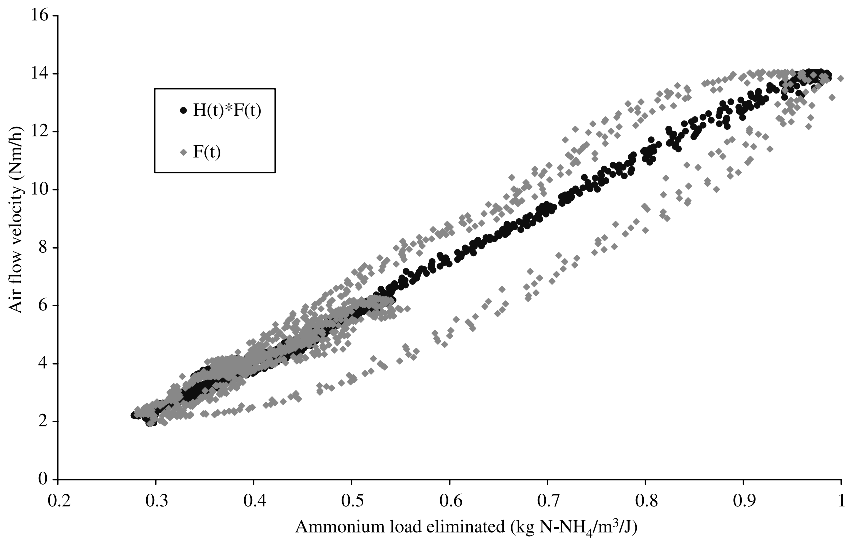

Figure 3 Air flow velocity function of eliminated load value

phase delay function *H(t)* permits us to correct these omissions and to obtain a linearity (see Figure 3, $H(t) * F(t)$). The phase delay function can be represented by the mathematical form of a combination of perfect reactors, wherein one parameter is the air flow velocity.

Consequently, the eliminated load during the course of time ($C_{v,e}$) is equal to the difference between the applied load ($C_{V,Aww}$) and the residual load (C_{vs}) convoluted by H(t):

Calculation of eliminated load

$$Cv_e(t) = H(t)^* Cv_{A,WW}(t) - Cv_S(t + \Delta t) \tag{2}$$

This methodology allows us to obtain a linear relation between the air flow velocity and the eliminated load, calculated above. The open loop control law can hence be expressed in the following way:

Open loop control law

$$V_{air}(t) = \alpha \cdot (H(t) * Cv_{AWW}(t) - Cv_{set}(t + \Delta t)) + \beta \tag{3}$$

It should be noted that the term $Cv_{set}(t + \Delta t)$ allows us to anticipate a future variation of the set-point for the residual load at the outlet. This solution can offer a non negligible flexibility with respect to the optimisation of the operation of a treatment plant.

Finally, to compensate for the errors of the feed forward control law or for the non-measurable disturbances, it is generally necessary to add a retroactive term. Open loop and feedback control displayed better results than a Feed Forward or Feed Back controller alone. The controller used for the retroactive loop is a Predictive Functional Control, PFC, (Richalet, 1993). One of its improvements lies within the choice of the manipulated parameters for the error determination (Equation 4). In fact, not the concentration in the outlet but the residual load is used and hence also a "set-point load", C_{Vset}:

Error calculation

$$error(t) = Cv_S(t) - Cv_{set}(t) \tag{4}$$

It can be seen that the set-point will vary with the feed flow rate and the controller, hence, takes this disturbance implicitly into account.

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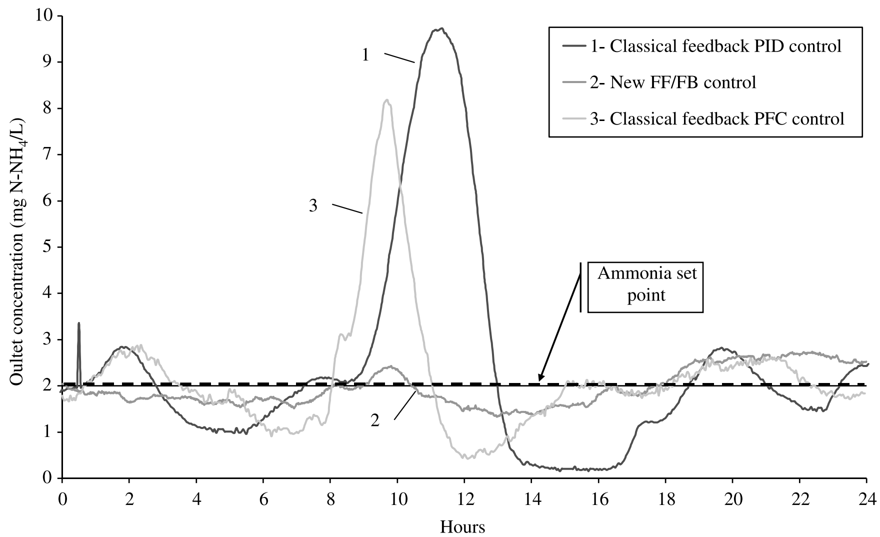

Figure 4 Comparison of control concepts at constant flow rates, NH_4-N outlet

Results and discussion

In order to evaluate the improvements generated by the developed control law, three different tests have been carried out: the first compares the efficiency of different control concepts at constant feed flow rate and fixed recirculation ratio. The second illustrates the performances at variable feed flow rate and fixed recirculation ratio. Finally, the third test scenario applies variable feed flow rates and a variable recirculation ratio.

In Figure 4 the responses of 3 control systems are depicted: PID, standard PFC (using DO and NH_4-N in the outlet) and the developed one (FF/FB). With a hydraulic retention time in the filter of around 2 hours, the PID and PFC controllers are not able to reject completely the disturbances linked to the variation of the effluent. This induces concentration peaks in the outlet concentration during the daily peak flow period and a phase of over-aeration just after the peak, which has a negative impact on the denitrification performance (not shown).

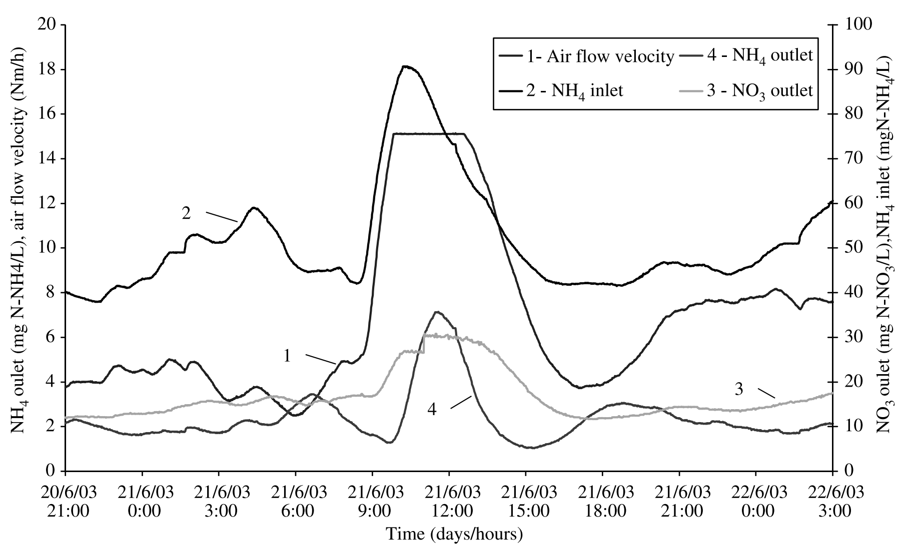

Figure 5 FF/FB control at variable feed flow rate and constant recirculation ratio

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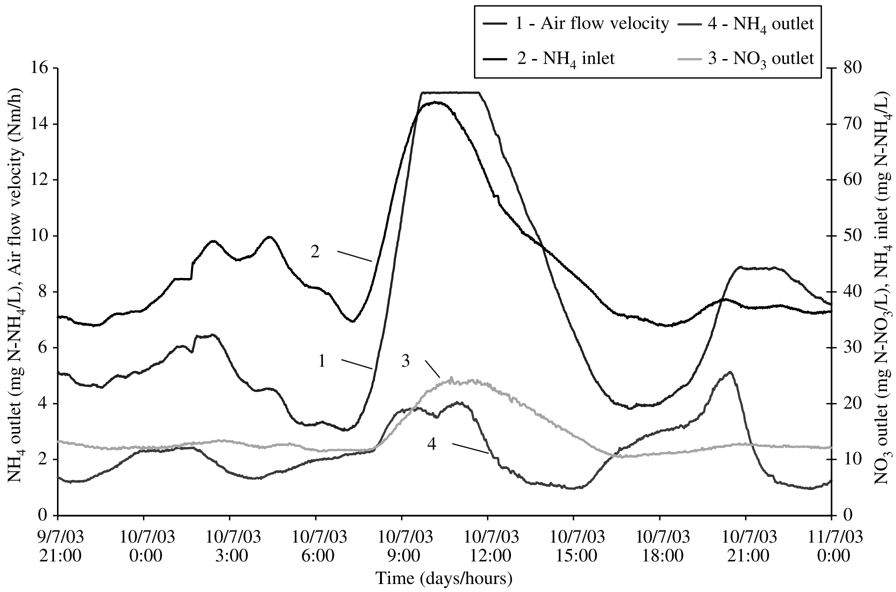

Figure 6 FF/FB control at variable feed flow rate and variable recirculation ratio

The correct estimation of the air requirement applying the FF/FB control permits us to reject this peak and also to avoid the period of over aeration.

For the conditions with variable feed flow rate (Figure 5) the FF/FB control functions correctly and anticipates the peak load. The short peak of the NH_4-N concentration in the outlet is not due to a bad set-point tracking but due to the fact that the applied load reached the level of maximum aeration capacity of the system. It has to be noted that a maximum level for the air flow rate was implemented in order to stay within the economical feasible limits of full scale installations.

Finally, also for the conditions with variable feed flow rate and variable recirculation ratio the developed FF/FB controller exhibits a superior performance compared to the other controllers tested (Figure 6). The FF/FB controller performs less well compared to the other scenarios but is has to be stressed that this last scenario is a test for extreme conditions, and is not representative for industrial scale plant operation.

Conclusions

The pilot plant tests realised have confirmed that simultaneous N/DN BAF systems react very sensitively to the aeration control strategies applied. Poorly adapted control strategies induce a strong decrease in treatment efficiency. This can result in several consequences, such as: non–respect of the effluent criteria, decrease in aeration efficiency and hence increase in energy consumption (costs), and for the case with denitrification with external carbon source (methanol) addition also of an increase in the required quantity of methanol.

These types of difficulties have been encountered with the PID type controllers used until now. The strategy proposed consists of a controller using ammonia measurements in the inlet and outlet: a Feedback/Feedforward block. Passing by a calculation of the load to be eliminated, an estimation of the air flow velocity to be applied is carried out dynamically. A retroactive loop corrects this prediction in order to reach exactly the desired set point.

The employment of this strategy is necessary once the effluents to be treated exhibit strong variations (peak load coefficient larger than 2.3) as it permits us to anticipate the

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evolution of the influent and hence the air requirements. The improvement in performance obtained with this strategy cover +5% increase in nitrogen removal and a reduction of 15 to 20% in air requirement. This offers rapid return of investment costs.

The principal benefit of this control strategy lies within its more precise control of the process. This offers new perspectives with respect to operation, through the diminution of the period characterised by "over-quality" or "under-quality" of the treated water.

Reducing the variation of the outlet concentrations permits us to limit the global "over quality", normally linked to safety factors. For example, in order to stay always below 5 mg NH_4-N/L, classically, one might aim at concentration in the outlet of 2 mg NH_4-N/L. With the proposed controller the set point can be set higher than 2 mg/L and hence substantial benefits can be gained, still respecting the effluent criteria.

In cases where the effluent criteria are based on daily average measurements, the strategy offers the flexibility to establish set points, taking into account the energy tariffs during the whole day and hence optimising the operational costs. These perspectives and benefits rely of course on the quality level of the service surrounding: air production, control valves etc. Although being able to determine the appropriate set-points, they also have to be applied correctly in order to benefit from the improved control strategy.

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