Optimum aerobic volume control based on continuous in-line oxygen uptake monitoring

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Abstract Dynamic adaptation of the aerated volume to changing load conditions is essential to maximise the nitrogen removal performance and to minimise energy consumption. A control strategy is presented which provides optimum aerobic volume control (OAV-control concept) based on continuous in-line oxygen uptake monitoring. For ammonium concentrations below 1 mg/l the oxygen uptake rate shows a strong and almost linear dependency on the ammonium concentration. Therefore, the oxygen uptake rate is an ideal indicator for the nitrification performance in activated sludge systems. The OAV-control concept provides dynamic variation of the minimum aerobic volume required for complete nitrification and therefore maximises the denitrification performance. In-line oxygen uptake monitoring is carried out by controlling the oxygen concentration in a continuous aerated zone of the aeration tank and measuring the total air flow to the aeration tank. The total air flow to the aeration tank is directly proportional to the current oxygen uptake rate and can therefore be used as an indicator for the required aerobic volume. The instrumentation requirements for installation of the OAV-control are relatively low, oxygen sensors in the aeration tank and an on-line air flow measurement are needed. This enables individual control of aeration tanks operated in parallel at low investment costs. The OAV-control concept is installed at the WWTP Linz-Asten (1 Mio PE) and shows very good results. Full scale results are presented.
Keywords Activated sludge process; aeration; aerobic volume; control; nitrification; respirometry

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Introduction

Theoretical background

At varying load conditions maximum nitrogen removal requires a dynamic adoption of the aerobic aeration tank volume. At all times the aerobic volume required for complete nitrification has to be provided in order to maximise the autotrophic population. The remaining volume can be used for denitrification.

Aerobic carbon degradation and nitrification are the two main processes which lead to oxygen consumption in the activated sludge process. Nitrifying bacteria reach 80% of their maximum growth rate already at an ammonia concentration of $c_{NH4\text{-}N} = 2$ mg/l (Figure 1). Eq. (1) gives the dependence of the current nitrification rate r_N on the ammonium concentration. In activated sludge systems the half saturation value for ammonium for autotrophic growth K_N is in the range of 0.2–0.8 $mg_{NH4\text{-}N}$/l. As stated in Eq. (2), the current nitrification rate r_N is directly proportional to the oxygen uptake rate due to nitrification OUR_N.

$$r_N = r_{MAX} \times \frac{S_{NH}}{K_N + S_{NH}} \qquad (1)$$

$$OUR_N = (4.57 - Y_A) \times r_N \qquad (2)$$

In a nitrifying activated sludge system a variation of the ammonia concentration in the aeration tank in the range $0 \le S_{NH} \le 1$ $mg_{NH4\text{-}N}$/l is linked to a significant change of the oxygen demand. The oxygen uptake rate is therefore an ideal indicator for the performance of the nitrification process in an activated sludge process. In contrast, the oxygen consumption due to carbon degradation is almost time-invariant in the nitrification zones of an activated sludge system. Readily biodegradable substrate entering the aeration tank – which leads to a short term change of the oxygen uptake rate for carbon degradation – is immediately consumed in anoxic zones of the aeration tank and therefore not available in nitrification zones (Brouwer *et al.*, 1998).

In-line oxygen uptake rate monitoring

For a continuously stirred reactor (CSTR) containing activated sludge the oxygen supply OC required to maintain a constant oxygen concentration is directly proportional to the current oxygen uptake rate OUR (Eq. (3)), which is a function of the air flow to the reactor (Eq. (4)).

$$\mathrm{OC} = \mathrm{OUR} \times \mathrm{V_{CSTR}} \times \frac{c_S}{c_S - S_O} \tag{3}$$

In an oxidation ditch type aeration tank in-line oxygen uptake monitoring can be carried out utilising an oxygen sensor in a continuously aerated zone. On condition of a constant oxygen concentration S_o in the continuously aerated zone a linear dependency between the required air flow to the aerators of the continuously aerated zone and the current oxygen uptake rate is determined by Eq. (4).

$$\mathrm{OUR} = \frac{Q_{\mathrm{AIR}}}{V} \times \rho_{AIR} \times y_{\mathrm{O2,AIR}} \times \mathrm{SOTE} \times \frac{(c_S - S_O)}{c_S} + \frac{A_{\mathrm{CHANNEL}} \times v_{\mathrm{CIRC}}}{V} \times S_{\mathrm{O,IN}} \tag{4}$$

The last term in Eq. (4) describes the contribution of oxygen transport into the continuously aerated zone due to the circulation flow in the tank. It is assumed that this contribution is constant, which can be achieved if the switching sequence of the diffuser arrays is set according to Figure 2. The diffuser array upstream of the continuously aerated zone is active only during high load periods. In this case the ammonium concentration is at a level where the nitrifiers are close to their maximum growth rate. Subsequently the oxygen uptake rate is high and the oxygen supplied in the zone upstream of the continuously aerated zone is consumed along the flow path between these two zones.

The air flow to the aeration tank is continuously monitored providing an on-line signal proportional to the current OUR. This signal is used to control the distribution of air to the diffuser arrays of the aeration tank. As a consequence, the aerobic volume is continuously adjusted to the actual oxygen demand and subsequently to the ammonia concentration.

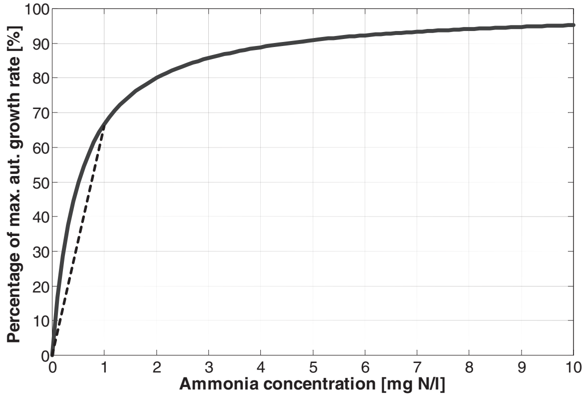

Figure 1 Dependence of the maximum autotrophic growth rate on the ammonia concentration

Practical realisation of the optimum aerobic volume control concept

Figure 2 shows a scheme of the proposed aeration control concept. A central blower station supplies all diffuser arrays of the oxidation ditch type aeration tank. An oxygen probe is installed in the continuously aerated zone, forwarding the current oxygen concentration to the blower controller. If the oxygen concentration in the continuously aerated zone drops below the set-point concentration the output air flow of the blowers is increased. The total air flow of the blowers is monitored continuously (Q_{AIR}). The maximum air flow to each diffuser array ($Q_{DA.i}$) is limited by the number of aerator elements installed in each array and the maximum air flow to a single aerator element, respectively.

During low loading periods only the continuously aerated zone (DA.C) is active. If the required airflow to maintain a constant oxygen concentration in the continuously aerated zone exceeds a user definable threshold value an additional diffuser array (DA.1) is switched on.

The threshold value of each diffuser array is depending on its size – which defines the maximum air flow to the diffuser array – and can be set by the operating personnel (threshold value $= k \times Q_{DA.C}$; $0 < k < 1$).

The available airflow is distributed to the two active arrays (DA.C and DA.1). If the required airflow is still increasing and exceeds the subsequent threshold value ($Q_{AIR} > k \times (Q_{DA.C} + Q_{DA.1})$) the next diffuser array (DA.2) is switched on. If the required airflow is further increasing the last diffuser array (DA.3) is switched on in case the last threshold value ($Q_{AIR} > k * (Q_{DA.C} + Q_{DA.1} + Q_{DA.2})$ is exceeded.

Decreasing nitrogen load causes a reduction of the OUR which leads to a lowering the aeration. If the airflow to the aeration tank drops below the threshold value of a specific diffuser array, it is shut off. This leads to a stepwise reduction of the aerobic tank volume in reverse order.

The control concept requires the installation of oxygen probes only in order to provide optimum aerobic volume control under dynamic load conditions. This is especially advantageous if a treatment plant includes parallel aeration tank lines. The air supply to each tank is automatically adapted to its individual load, even if the load split to the parallel lines is not perfectly symmetric.

In case classic ammonium control is applied at a treatment plant with parallel treatment lines an on-line ammonium measurement is required for each of the parallel aeration tanks in order to enable individual control of each tank. Additionally, oxygen sensors are required, which – in this case – serve for controlling the oxygen concentration in the aeration tanks within an economic range.

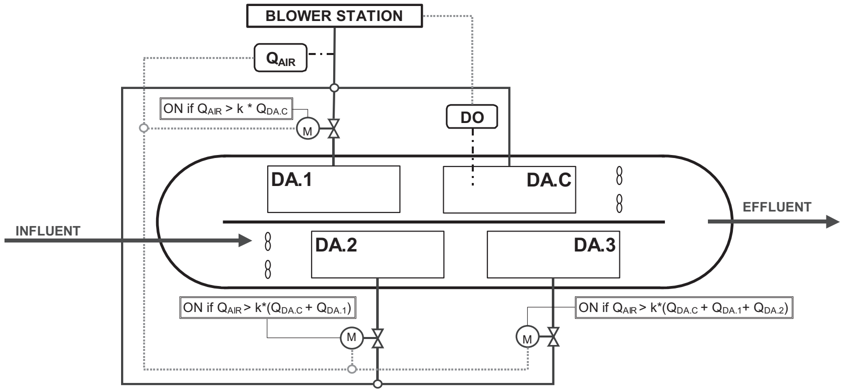

Figure 2 Basic scheme of the optimum aerobic volume control concept

For safety reasons an on-line ammonium measurement can also be integrated into the OAV-concept – the aeration is fully turned on in case the ammonium concentration in the effluent channel of the aeration tank(s) exceeds a maximum threshold value.

Material and methods

Case study: WWTP Linz-Asten

The presented control concept has been installed at the WWTP Linz-Asten (1 Mio PE) and will be installed at the extended main Vienna WWTP (4 Mio PE, operation starting in 2005).

A layout of WWTP Linz-Asten is given in Figure 3, after being extended in 1999–2001 it is a single stage activated sludge plant where the aeration tanks are built as two stages of oxidation ditch type tanks in series. The plant in its previous configuration went into operation in 1982. The mechanical treatment stage included a screening station, grit chamber and primary clarification. The biological treatment stage included four parallel oxidation ditches – with a volume of $V = 11{,}000\ m^3$ each – and eight circular final clarifier tanks – with a volume of $V = 8{,}750\ m^3$ each. Due to load increase and since the plant receives a considerable amount of industrial wastewater – which led to nitrification inhibition and other operational problems (Schweighofer *et al.*, 1996) – a plant extension became necessary.

The extended plant has been designed for the following loads: COD = 80 t/d, TKN = 11.2 t/d and TP = 1.84 t/d. The average dry weather flow is 220,000 m^3/d, the peak hydraulic load is 8.8 m^3/s.

The effluent requirements are: COD < 90 mg/l, NH_4-N < 5 mg/l, NO_3-N < 15 mg/l, TP < 1 mg/l. For temperatures above $T = 12°C$ the nitrogen removal performance – calculated on a daily basis – has to reach a minimum of 60%.

In the course of the extension new fine screens with a gap width of 10 mm have been installed. Four additional aeration tanks – with a volume of $V = 12{,}000\ m^3$ each – and two aerobic selector tanks – with a volume of $V = 3{,}500\ m^3$ each – have been erected. The new tanks are operated in series with the existing tanks – with the new tanks operating as the first stage of the aeration tanks. The selector tanks have been included in the new concept in order to improve the sludge settling properties. The selector tanks can alternatively be operated as return sludge pre-aeration tanks. In this operational mode, the mechanically treated influent bypasses the selector tanks and is fed directly to the first stage aeration tanks. This mode of operation may be required if a strong nitrification inhibition is detected. In this case harmful concentrations of nitrification inhibiting substances can be avoided in the selector tanks.

Already in 1997–98 the final clarifier tanks have been reconstructed including a redesign of the influent and effluent construction and an increase of the water depth to 3.9 m – which resulted in an increase of the final clarifier volume of 25%.

In each aeration tank stage four tanks are operated in parallel. In the first stage, the mechanically treated influent is split up into the four tanks (AT 1–AT 4), which discharge into a common effluent channel. From this channel the mixed liquor is distributed to the four parallel aeration tanks of stage 2 (AT 5–AT 8). The total of eight final clarifier tanks is split into two groups of four tanks each, each group receives the effluent from two aeration tanks – AT 5 and AT 6 supplying one group and AT 7 and AT 8 the other. In each of the inlet channels to the two final clarifier tank groups an on-line ammonium analyser is installed. These analysers are installed for control purposes, in case the measured ammonium concentration exceeds a certain value the aeration of the respective line is fully activated.

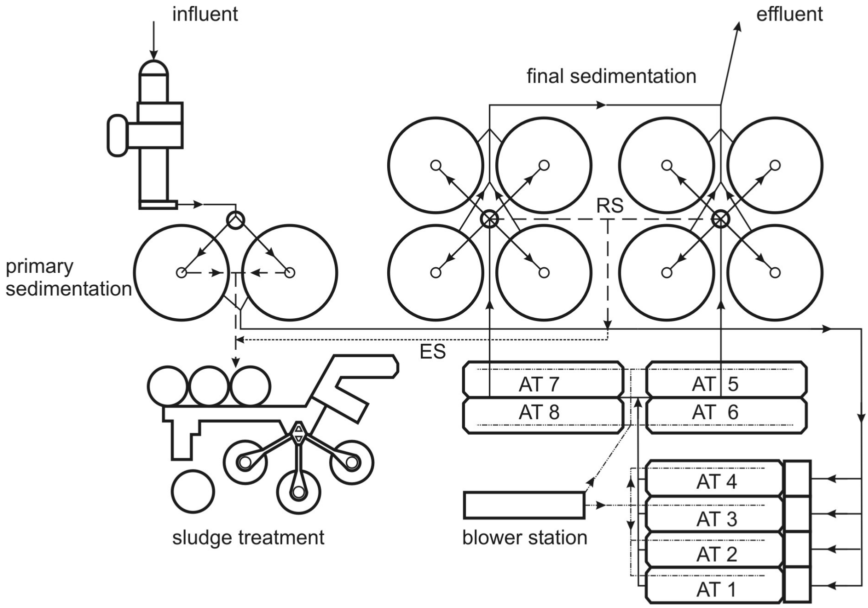

Figure 3 Layout of WWTP Linz-Asten

Operational data

For the performance investigation described below on-line and laboratory data from the full stage plant was used. During the performance evaluation period an *in-situ* ammonium/nitrate sensor (Rieger *et al.*, 2001) was installed in the influent channel to the second stage aeration tanks, providing an on-line signal for the ammonium concentration entering the second stage aeration tanks. The on-site ammonium analysers were used for monitoring the effluent ammonium concentration of the second stage aeration tanks.

Results and discussion

Performance investigation

Figure 4 shows the ammonium influent load, the total air flow and the ammonium effluent concentration of two subsequent days of the second stage aeration tanks of WWTP Linz-Asten. It clearly can be seen that an increase of the ammonium influent load immediately results in an increase of the air flow to the aeration tanks. In case the air flow exceeds a threshold value the aerobic volume is increased by switching on additional diffuser arrays. Since at WWTP Linz-Asten each second stage aeration tank includes four equally sized diffuser arrays, the threshold values for switching on additional arrays are equidistant. It also can be seen that the controller parameters are adjusted well, since the switching frequency of the single diffuser arrays is low. The minimum time period between on and off-switching of a specific array is more than 30 minutes.

From the lower section of Figure 4 it can be seen, that complete nitrification is achieved up to an ammonium influent load to the second stage aeration tanks of 20 $kg_{NH4\text{-}N}$/h. Only during peak loads – which occurred on the first day during rain events – the ammonium effluent concentration reached peak values of up to 3 $mg_{NH4\text{-}N}$/l. These effluent concentrations could be lowered further, if a dynamic adjustment of the threshold values to the influent ammonium load could be integrated in the controller set up. This would lead to increased periods with maximum aerated volume and subsequently increase nitrification. The disadvantage of such a strategy would be a decreased overall nitrogen removal due to a decrease of the anoxic volume and an increased switching frequency of the diffuser array.

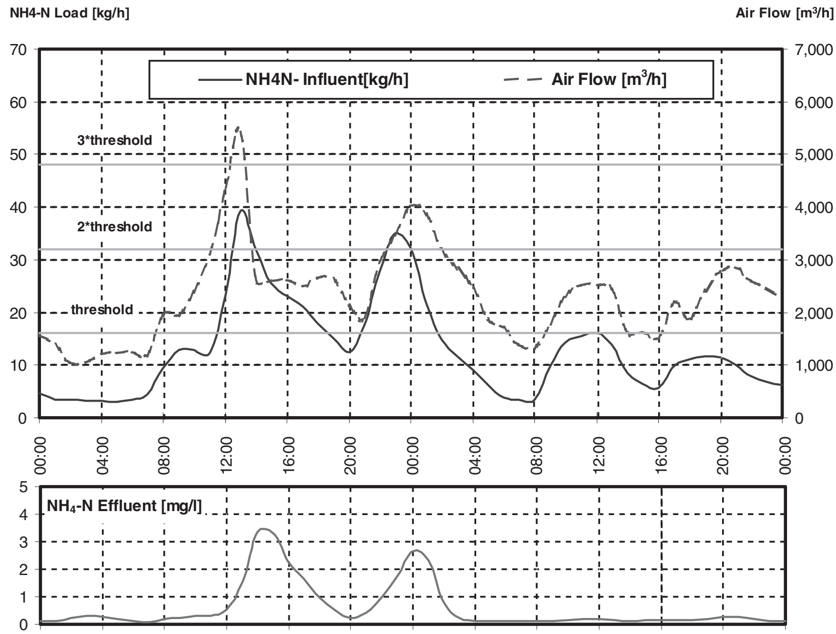

Figure 4 Ammonium influent load, total air flow and ammonium effluent concentration of the second stage aeration tanks of WWTP Linz-Asten on two subsequent days in November 2001

The current controller settings are optimised for dry weather conditions. During the second day in Figure 4 complete nitrification is achieved with a maximum of two active diffuser arrays. Consequently, a large anoxic volume is available on that day resulting in a high nitrogen removal performance.

Figure 5 shows in the upper graph the ammonium effluent concentration and the total nitrogen removal rate at WWTP Linz-Asten during September 2001. A very good effluent quality was achieved, the daily effluent ammonium concentrations exceeds 1 mg/l only on

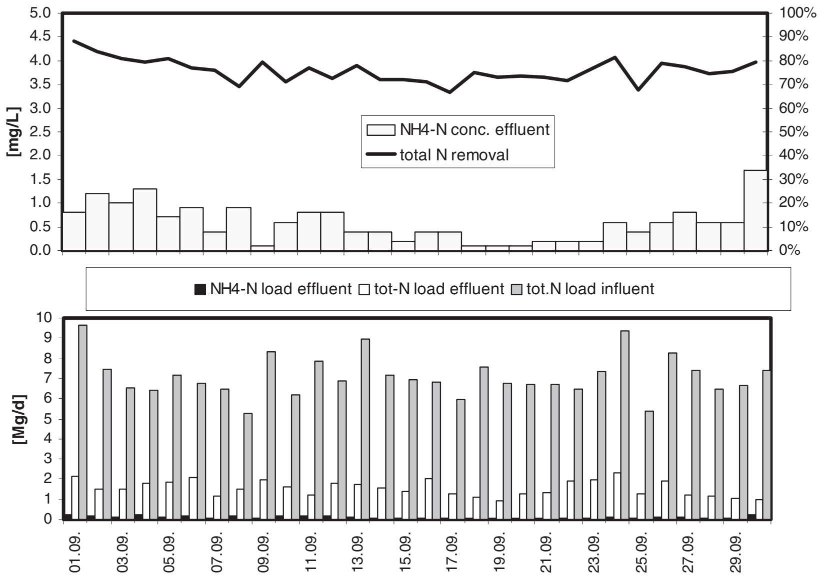

Figure 5 Ammonium effluent concentration and total nitrogen removal of WWTP Linz-Asten during September 2001

three days of the month. The nitrogen removal rate was maintained well above the legal requirement of 60%, values ranged from 70 to 80%.

The lower graph of Figure 5 shows a comparison of the influent and effluent nitrogen load of WWTP Linz-Asten during September 2001. The total nitrogen influent load follows a similar trend to the total nitrogen removal rate. This means, that the plant is capable to treat ammonium peak loads, an increase of the influent load responds to only a small increase of the total nitrogen effluent load which results in an increased nitrogen removal rate. The ammonium effluent load is always very low, in general it is in the range of 10% of the total nitrogen effluent load.

Conclusions

The optimum aerobic volume control concept (OAV-control concept) is a simple and smart control strategy providing a dynamic adaptation of the aerobic volume required for complete nitrification while the anoxic volume is simultaneously maximised. It uses the signal of a continuous air flow measurement as indicator for dynamic adjustment of the aerobic volume. Installation is based on standard equipment generally available at wastewater treatment plants – an oxygen sensor in the aeration tank and an on-line measurement of the air flow to the aeration tank are required.

The OAV-control concept is operated for almost one year now at the WWTP Linz-Asten (1 Mio. PE) and has proved to perform very successfully. A full scale performance evaluation study showed that the in-line oxygen uptake measurement strongly correlates to the influent ammonium load to the aeration tanks. The ammonium effluent concentration was below 1 mg/l and the total nitrogen removal rate ranged from 70% to 80%. Further it was shown that the control leads to ample capacity to treat ammonium peak loads, a substantial increase of the influent load resulted in only a moderate increase of the effluent nitrogen load.

Nomenclature

$A_{CHANNEL}$	Cross section area of the oxidation ditch, [m^2]
c_S	Oxygen saturation concentration, [mg_{O2}/l]
d_S	Diffuser submergence, [m]
k	Factor for variation of the threshold values for on/off switching of the switch able aerated zones
K_N	Half saturation constant for ammonium for autotrophic growth, [$mg_{NH4\text{-}N}/l$]
OC	Oxygen supply, [g_{O2}/h]
OUR	Total oxygen uptake rate, [$mg_{O2}/(l*h)$]
OUR_N	Oxygen uptake rate for nitrification, [$mg_{O2}/(l*h)$]
Q_{AIR}	Air flow, [$m^3{}_{N,AIR}/h$]
$Q_{DA.C}$	Air flow to the continuously aerated zone
$Q_{DA.i}$	Air flow to each of the switch able aerated zones
r_N	Current nitrification rate, [$mg_{NH4\text{-}N}/(l*h)$]
ρ_{AIR}	Air density, [kg/m^3]
r_{MAX}	Maximum nitrification rate, [$mg_{NH4\text{-}N}/(l*h)$]
S_{NH}	Ammonium concentration, [$mg_{NH4\text{-}N}/l$]
S_O	Oxygen concentration, [mg_{O2}/l]
$S_{O,IN}$	Oxygen concentration of incoming flow, [mg_{O2}/l]
SOTE	Standard oxygen transfer efficiency, [%]
V	Volume of the continuously aerated zone, [m^3]
v_{CIRC}	Circulation flow speed in the oxidation ditch, [m/h]
V_{CSTR}	Volume of the continuously stirred reactor, [m^3]

Y_A	Autotrophic yield, [$mg_{COD(XA)}/mg_{NH4\text{-}N}$]
$y_{O2,\,AIR}$	Oxygen fraction in air, [%]

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