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# 'Swinging ORP' as operation strategy for stable reject water treatment by nitritation–anammox in sequencing batch reactors

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ABSTRACT

A single stage nitritation–anammox pilot scale SBR was implemented to treat reject water from sludge dewatering. The SBR was operated with a new strategy, a combination of interval feeding with interval aeration using the oxidation–reduction potential (ORP) as the main process indicator parameter. The strategy allowed for optimized treatment of high nitrogen loaded reject water providing stable operation and achieving a nitrogen removal efficiency of more than 90% at a volumetric nitrogen load of 400 g N $m^{-3}$ $d^{-1}$. COD removal was also observed with an efficiency of around 70%.

The concept of interval feeding monitored by the ORP also allowed for adjustments to changing environmental conditions (i.e., decrease in temperature) by adjusting the number of intervals per cycle and the number of cycles per day. The distinct swing in the ORP signal which showed the largest amplitudes and most distinct pattern of all monitored parameters made the ORP the most favorable control parameter for nitritation–anammox in this type of SBR.



## 1. Introduction

Completely autotrophic nitrogen removal has been studied extensively as an alternative nitrogen removal pathway in wastewater treatment since the discovery of anaerobic ammonium oxidation (anammox) in the 1990s [1]. This process comprises partial aerobic conversion of ammonium to nitrite (nitritation) with anoxic conversion of ammonium and nitrite to di-nitrogen gas (anammox reaction) by a specific group of microorganisms belonging to the phylum of the Planctomycetes [2,3]. The reduced oxygen requirements and no need for organic carbon make this process especially interesting from an engineering perspective [4,5]. Operational costs for nitritation–anammox processes are significantly lower compared to current treatment technologies based on conventional nitrification/denitrification [6,7]. Especially interesting are applications in wastewater treatment systems with high ammonium concentration such as supernatant from anaerobic digestion or certain industrial wastewaters.

Nitritation–anammox has been studied in a large number of lab and pilot scale reactors [8–12] over the past decade under various aspects [13]. Within recent years large scale implementation of various anammox [14] and nitritation–anammox [7,15,16] technologies have been developed. Due to the low growth rate of anammox bacteria biomass retention is very important and has influenced reactor configurations; thus, biofilm or granule based systems are most commonly used.

Increasing numbers of large scale installations, e.g., reactor types for single stage nitritation–anammox such as moving bed biofilm reactors (MBBRs) [16], granular sludge processes [17] and SBRs [7,15] demand more answers for more practical issues such as influence/importance of temperature (reported optimal temperature >30 °C [18,19]), or the effect of bioavailable COD in the sludge water [20,21].

Large scale systems also rely on stable operation provided by a robust control strategy. Especially for SBRs, the control strategy and operation regime are crucial for a successful single stage nitritation–anammox process. Several research groups have developed possibilities for such controls: a pH based control strategy was proposed by Wett [7] and has been implemented successfully at several sites (e.g., Strass in Austria; Heidelberg, Plettenberg in Germany; Thun, Glarnerland in Switzerland). In Zurich, Switzerland, the partial nitritation anaerobic ammonium oxidation process (PNAA) which relies on online measurements of ammonium, nitrate and oxygen was developed by Joss et al. [15].

Large scale granular reactors, as described, e.g., in Abma et al. [17], are operated with continuous aeration which is controlled by measurements of ammonium and nitrite in the effluent. For MBBRs electrical conductivity has also been investigated as monitoring parameter in one and two stage nitritation–anammox systems [22].

The oxidation–reduction potential (ORP), however, has not been studied or applied to control nitritation–anammox systems. In combination with pH, the ORP has been widely used as control

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**Table 1**
Summary of the SBR operation parameters: number of cycles, intervals, feeding and reaction times, exchange ratios, and air flow rates.

| | Period I (day 0–106) | Period II (day 106–161) |
|---|---|---|
| Cycles per day | 5 | 3 |
| Intervals per cycle | 4 | 6 |
| Feeding time per interval | 2 min | 2 min |
| Reaction time per cycle | 255 min | 450 min |
| Ratio of aerobic/anoxic time | 0.89 | 0.83 |
| Settling time | 25 min | 20 min |
| With drawl | 8 min | 10 min |
| Exchange ratio[a] | 7.0 ± 1.4% | 9.8 ± 1.3% |
| Total suspended solids[b] | 5.0 ± 1.0 g/L | 5.1 ± 0.4 g/L |
| Air flow during aeration | 0.6–0.8 $m^3$/h | 0.8–0.95 $m^3$/h |

[a]The exchange ratio is defined as $f_r = \Delta V/\Delta V + \Delta V_{min}$ with $\Delta V$ being the volume added per cycle (exchange volume) and $V_{min}$ the minimal reactor volume.
[b]Volatile suspended solids (VSS): 65 ± 1.3%.

parameter for online monitoring and control of nitrification and denitrification since the 1980s [23–29] which proved its values as a signal for process conditions.

This study presents a new approach to achieve stable operation of a single stage nitritation–anammox SBR based on interval feeding combined with interval aeration using fixed interval length and ORP monitoring. It is demonstrated that the ORP is a potential control parameter when the operation regime does not provide distinct gradients for other parameters, such as pH or oxygen.

## 2. Material and methods

### 2.1. Pilot-plant operation

During a start-up phase of nearly three months a pilot SBR (diameter 570 mm, height 820 mm, $V_{min}$ = 140 L) was operated with activated sludge and municipal wastewater from the Garching wastewater treatment plant, Germany (data not shown). Feed was then switched to reject water from the anaerobic sludge digestion and the SBR was inoculated with 1/3 vol% of nitritation–anammox sludge from the full-scale plant in Werdhölzli (Zurich, Switherland) [15] (day 0) and from there on continuously operated with reject water.

Fig. 1 shows the reactor setup: the reject water was stored in a 1.5 $m^3$ storage tank and pumped into the SBR automatically at the start of each interval. Aeration was provided with ceramic membranes at 2.5 bar air pressure with an air flow rate of 600–1000 L $h^{-1}$. The air flow rate was manually adjusted to establish oxygen concentrations of 0.3–0.5 mg $L^{-1}$ during the aeration phases without any further control. Flow rates had to be adjusted according to the nitrogen loading rate. ORP (Pt-electrode with a silver/silver chloride reference electrode and 3 M KCl as electrolyte), pH, temperature, dissolved oxygen (DO) and conductivity were measured online. The DO, pH, and ORP electrodes were cleaned weekly, and no drift in the ORP signal was observed over the duration of the experiment. The SBR was controlled with timers and level controls for effluent withdrawal, set to the same minimum volume ($V_{min}$ = 140 L), at the end of every cycle and for overflow prevention. The operating temperature was maintained between 28 and 30 °C if not stated otherwise.

### 2.2. SBR operation

SBR operation was implemented solely based on timers. At this point no parameter based control (e.g., DO or ORP set-points) was used. Two different strategies were applied (see Fig. 2 and Table 1): in period I (days 0–106, temperature 30 °C) the reactor ran with 5 cycles (of 4.8 h) per day and 4 intervals per cycle (20 intervals per day).

Each cycle started with 2 min feeding introducing 2.1 ± 0.4 L reject water. The influent volume was constant during one cycle and was adjusted only to balance variations in nitrogen loading. After the influent followed a mixing phase of 28 min (total mixing time 30 min) and an aeration phase of 30 min. These 3 steps (one interval of 60 min) were repeated 4 times and then followed by a last post-mixing phase of 15 min. Settling time was set to 25 min, the time for effluent discharge was 8 min with. Each cycle then had a reaction time of 255 min with a ratio of aerobic/anoxic time of 0.89.

A decreased in temperature to 26–28 °C was introduced on day 106. Operation was changed to 3 cycles (with 8 h) per day and 6 intervals per cycle (18 intervals per day). In this setup the cycle started again with a 2 min feed (2.5 ± 0.3 L) followed by a 34 min mixing period (36 min total mixing time). The aeration phase was 34 min resulting in 70 min intervals. After repeating these steps 6 times a last mixing phase of 30 min, a settling time of 20 min and 10 min for effluent discharge concluded the cycle. The reaction time in this 8 h cycle was 450 min with a ratio of aerobic to anoxic time of 0.83 (period II).

### 2.3. Analytical methods

Standard cuvette tests (Hach Lange GmbH, Germany) analyzed with a spectrophotometer (DR 2800, Hach Lang) were used for $NH_4$–N (LCK 303), $NO_2$–N (LCK 342), $NO_3$–N (LCK 339), and COD (LCK 514). The analytical methods used for TKN (Total-Kjeldahl-Nitrogen) and $BOD_5$ are described in the “German Methods for Water-, Wastewater- and Sludge Analyses” (DEV, 2010). Concentrations of total suspended solids (TSS) were measured after filtration and drying at 105 °C. Temperature and pH were measured by instruments from WTW GmbH, Germany.

## 3. Results

### 3.1. Reactor performance

Fig. 3 shows the reactor performance over time during the course of the experiments after addition of the seed sludge (day 0). Effluent $NH_4$–N values dropped below 50 mg $L^{-1}$ in period I ($T$ = 30 °C) and slightly increased again at the end of period II (26–28 °C) (Fig. 2A). In period I an average of 35 ± 20 mg $L^{-1}$ $NH_4$–N and 17 ± 7.1 mg $L^{-1}$ $NO_3$–N was detected in the effluent; period II gave average values of 42 ± 18 mg $L^{-1}$ $NH_4$–N and 52 ± 20 mg $L^{-1}$ $NO_3$–N (Table 2). This corresponded to more than 95% $NH_4$–N and more than 90% total nitrogen removal. Fig. 2B shows the COD influent and effluent concentrations over time. On average, 278 mg $L^{-1}$ (period I) and 220 mg $L^{-1}$ (period II) were detected (Table 2), which resulted in an average COD elimination of 71% and 74%, respectively. The C/N ratio was low (around 0.8) with a COD/$BOD_5$ ratio of around 9.

An average volumetric total-nitrogen load of 400 g N $m^{-3}$ $d^{-1}$ was measured and the average volumetric COD load achieved was 315 g COD $m^{-3}$ $d^{-1}$ throughout periods I and II. The sludge loads were 83 g N kg $TSS^{-1}$ $d^{-1}$ and 66 g COD kg $TSS^{-1}$ $d^{-1}$, respectively. Optimal operating conditions were achieved at a nitrogen sludge load of 85.5 g N kg $TSS^{-1}$ $d^{-1}$ at 423 g N $m^{-3}$ $d^{-1}$ volume specific nitrogen removal rate. The corresponding removal efficiency was 94%.

### 3.2. The ‘swinging ORP’ as operation strategy

The concept of the Swinging ORP is based on time controlled interval feeding in conjunction with interval aeration during one SBR cycle. Fig. 4 shows examples of characteristic profile patterns of ORP but also the signals of conductivity, DO, and pH on day 22