Process optimization and energy reduction with online controls by analysing nitrification / denitrification rates in a continuous flow SBR

ABSTRACT

The biological wastewater treatment step plays a critical role in providing the capacity necessary for achieving biochemical oxygen demand (BOD) and nutrient removal targets. Biological process optimization can improve treatment plant reliability and help meet current and future regulatory requirements while at the same time minimizing energy consumption. This paper shows how nitrification and denitrification rates can be monitored online in a biological treatment step and used to improve process and energy performance. Nitrification and denitrification rates were monitored at two SBR wastewater treatment facilities in Sweden and Wisconsin, USA, using online probes measuring ammonia-N (NH_4), nitrate-N (NO_3), dissolved oxygen (DO), total suspended solids (TSS), temperature and water level. Besides being used as a health check of the process, the rates can be used to calculate real time required sludge age for nitrification. When using this knowledge of the process requirements at one of the two facilities, the sludge age was reduced by 50% without affecting the treatment performance of the plant. This demonstrates how online nitrification and denitrification rates can be used both for evaluating the health of a treatment process and optimizing energy consumption.

INTRODUCTION

Activated sludge is a biological treatment process used to remove nutrients from the influent wastewater stream. In typical domestic wastewater systems, total kjeldahl nitrogen (TKN), consisting of organic nitrogen and ammonia nitrogen, enters the plant. The organic nitrogen is converted to NH_4 through ammonification, while the ammonia is converted to nitrite (NO_2) and subsequently NO_3 through the nitrification process. The processes occur under aerobic conditions and are greatly dependant on temperature, sludge age, pH, DO concentration and alkalinity (Randall et al, 1998). The autotrophic bacteria responsible for nitrification are more susceptible to toxicity and are slower growing microorganisms. Their sensitivity combined with aeration being the single most energy consuming process step in wastewater treatment (Olsson, 2008) implies a great potential for process performance improvements by carefully monitoring and optimizing the biological conditions for nitrification.

Denitrification is the step in which nitrate nitrogen is converted to nitrogen gas. The process occurs under anoxic conditions and is dependent on temperature and an available carbon source. The heterotrophic bacteria responsible for denitrification use chemically bound oxygen in lieu of dissolved oxygen, which results in 2.8 grams of BOD removal per gram of nitrate denitrified (U.S. Environmental Protection Agency, 1993).

Sanitaire was invited by the plant operators to add the IQ SensorNet system to the previously installed control system at the Cedar Grove wastewater treatment facility in an effort to better understand the plant's operation by analysing nitrification and denitrification rates. To support the results from this plant, monitoring of nitrification and denitrification rates combined with operational changes were conducted at an SBR pilot plant located at a test facility in Hammarby Sjöstadsverk, Sweden.

MATERIALS AND METHODS

Test sites

Nitrification and denitrification rates were monitored at two wastewater treatment facilities. The first site is a pilot site, placed in the test facility Hammarby Sjöstadsverk in Sweden. The pilot plant flow is paced at a percentage of the wastewater that is being processed by the main WWTP for the city of Stockholm. The other facility is a full scale wastewater treatment plant located in Wisconsin, USA called Cedar Grove.

Both sites utilize the Sanitaire Intermittent Cycle Extended Aeration System (ICEAS) technology, which is an activated sludge sequencing batch reactor (SBR) process with continuous inflow. The ICEAS bioreactor is divided into a pre-react zone and a main react zone. While the majority of the basin volume is found in the main react zone, all influent first enters the pre-react zone. The separate zones allow the ICEAS system to have continuous inflow. The high food to mass ratio in the pre-react zone acts as a biological selector which discourages filamentous growth and encourages good settling floc formers and other healthy bacteria. The main process equipment, consisting of mixers, decanter and waste activated sludge (WAS) pumps, are placed in the main react zone while aeration extends through both zones.

An ICEAS cycle is generally 4.8 hours and is divided into a react phase, settle phase and decant phase. Depending on process requirements, the react phase includes anoxic and aerobic periods by alternating the use of the blower and mixer. Sludge is generally wasted from the basin each cycle during the decanting phase when the MLSS is the most concentrated.

The Cedar Grove facility was commissioned in 2006 and consists of two ICEAS basins. While the plant is designed for 400,000 gallons (1500 m^3) per day, it is currently only loaded with 150,000 gallons (570 m^3) per day. To treat the lower load, only one of the two parallel basins is currently in use. Having the flexibility to remove one of the two basins is possible due to the continuous flow of the ICEAS process. The plant doesn't currently have a total nitrogen permit, but the control system of the ICEAS reactor enables the flexibility to add anoxic periods to encourage denitrification.

The ICEAS pilot plant at Hammarby Sjöstadsverk is part of a full reuse pilot plant. The reuse plant is designed for 14.7 m^3 per day and was placed in operation during the summer of 2012. The biological treatment part of the plant consists of one ICEAS basin sized 1.5 x 4.7 m, designed according to the same principles as a full scale ICEAS plant. Being a pilot plant used for research and development at Xylem, the plant is profoundly monitored by both online and lab measurements, making it a good site for testing process optimization and control.

Online measurement of nitrification rate

Both plants used in this study were monitored with online equipment to enable evaluation of nitrification and denitrification rates. Online measured values of TSS, NH_4, NO_3, DO, temperature and oxidation reduction potential (ORP), along with analog data from a level transducer, were provided using a WTW IQ SensorNet system. The probes were mounted in the main react zone of the ICEAS basins, at a level to ensure adequate submersion even when the water level is at the lowest point.

The specific nitrification rate was calculated as mass of ammonia-nitrogen nitrified per aerobic time and mass of volatile suspended solids (VSS) [kg NH_4-N / kg MLVSS · aerobic hr]. In a similar manner, the specific denitrification rate was calculated as mass of nitrate nitrogen denitrified per anoxic time and mass of VSS [kg NO_3-N / kg MLVSS · anoxic hr]. The VSS was calculated based on the TSS probe at each site and a ratio between MLVSS and MLSS established from onsite labs at both plants. The volume of the tank was determined from the online level transducers combined with known basin areas.

Both nitrification and denitrification rates were calculated based on the change measured in the concentration of NO_3. Ammonia concentration in the ICEAS basin is influenced by the incoming ammonia stream, the incoming organic nitrogen being converted to ammonia and the decrease in ammonia due to nitrification. For this reason, measuring the decrease in ammonia as an indicator of nitrification will not give a representative value. The increase of NO_3 during aerobic conditions is however a more accurate indication of the rate of nitrification.

The ORP and DO probes in the ICEAS basins were used to verify the aerobic and anoxic conditions when evaluating the nitrification and denitrification rates. The calculated rates were temperature adjusted to 20 °C for ease of comparison to published values.

Calculation of nitrifier growth rate and required sludge age

Based on the observed specific nitrification rates, a specific nitrifier growth rate could be established. The growth rate was calculated according to Peng (2012) using the nitrifier yield coefficient, defined as grams of nitrifiers produced per gram of ammonia nitrogen nitrified, as well as a set quota for the percentage of active nitrifier VSS per total basin VSS. The later was based on the ratio of secondary biodegradable organic carbon to ammonia nitrogen as well nitrifier and heterotrophic yield coefficients (U.S. Environmental Protection Agency, 1993). Values used for the yield coefficients were 0.12 g VSS/g N and 0.60 g VSS/g cBOD.

The calculated growth rates were used to establish a minimum required sludge age, simply defined as the inverse of the nitrifier growth rate. A recommended sludge age was then calculated from the minimum sludge age by multiplying it with a safety factor of two. The actual sludge age used was monitored with the use of the basin TSS probe, as well as a TSS probe and flow measurement in the WAS line.

RESULTS AND DISCUSSION

Online calculations of nitrification and denitrification rates

Online measurements of ammonia, nitrate and DO during 24 hours at Cedar Grove is shown in Figure 1. Periods are marked during which nitrification and denitrification rates were calculated. As the DO measurements indicate, the graph is taken from a period during which the whole react phase was aerated. This resulted in constant nitrification during the react phase, while all denitrification occurred during the settle and decant period. During this study, the cycle structure at Cedar Grove was however changed for selected periods to include anoxic periods in the react phase. This enabled denitrification rate evaluation during both the react phase as well as the settle and decant period.

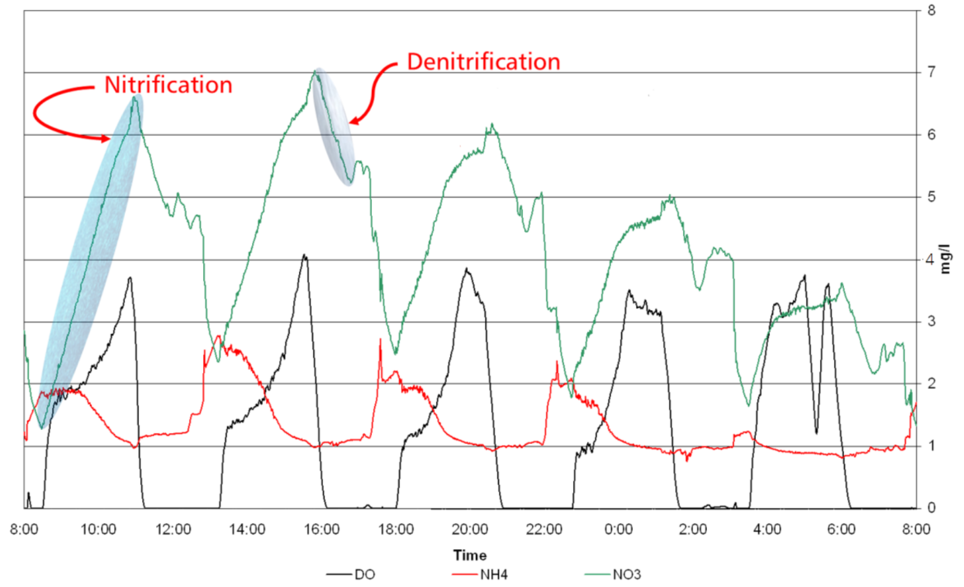

Figure 1: *Online measurements of NH_4, NO_3 and DO during 24 hours from Cedar Grove WWTP*

Figure 1 illustrates when automatic calculation of rates took place. Nitrification rates should be measured during aerobic conditions within a period when the nitrate shows a steady increase. The slope of the line is then equal to the nitrification rate. Cycles occurring during lower loads, as seen in the early morning cycles in the figure, don't show a steady increase of nitrate due to the limited ammonia substrate to be nitrified. For this reason, these cycles should not be used to calculate nitrification rates.

Online monitored nitrification rates during the period of August to October 2011 resulted in an average of 0.0025 kg NO_3-N/kg VSS · hr when corrected to 20 °C. Similar values were obtained for the calculated denitrification rates. These results are in the range of typical published rates (U.S. Environmental Protection Agency, 1993; U.S. Environmental Protection Agency, 2010)

Rates were calculated during both low loaded and high loaded parts of the day, as well as during different aerated periods during the react phase. Depending on when during the day the rates were calculated, the difference in available substrate caused some differences in the observed rate. The results show that rates should be calculated during the same period every day in order to compare different days and use the values for evaluation of the process.

Using nitrification rates to adjust the sludge age

To show an example on how online calculation of nitrification rates can be used to optimize a wastewater treatment process, calculations of the rates at the pilot plant at Hammarby Sjöstadsverk were combined with operational changes of the process.

Nitrification rates were first evaluated for one week once a stable sludge age was established. Measured and calculated values for this period are shown in Table 1. The average calculated nitrification rate of 0.0028 kg NO_3-N/kg VSS · hr matches well with published values. The calculated recommended sludge age of 6 days was significantly lower than the operating sludge age of 23 days. These results represent a possibility for optimizing the process.

After the measurement period, two operational changes were done to the process. As indicated by the calculations, the sludge age was reduced significantly. In addition, the DO set point was reduced from 4 mg/L to 2 mg/L. After a two week acclimation period, during which the process was allowed to stabilize, the nitrification rates were once again monitored for one week. Measured and calculated values from the second period are listed in Table 1.

The results show that the operational changes made to the process caused a reduction in nitrification rate and growth rate. However, the calculated recommended sludge age is now very close to the actual sludge age used. Given that the effluent ammonia concentrations during periods 1 and 2 are similar, the lower sludge age adjustment as a result of the online nitrification rate was still sufficient to treat the influent ammonia to the system.

Table 1: Measured and calculated values for two periods, each one week long, from Hammarby Sjöstadsverk, Sweden

	Measurements		Calculated values		
	Sludge age used	NH4 effluent	Nitrification rate, 20 °C	Nitrifier growth rate	Recommended sludge age
	Days	mg/l	kg NO_3-N/kg VSS*hr	Day^{-1}	Days
Period 1	23	0.08	0.0028	0.32	6.2
Period 2	12	0.19	0.0017	0.20	10

Process and energy benefits

The example from Hammarby Sjöstadsverk demonstrates how online monitoring of the nitrification rate can adjust the sludge age to the requirement of the system. Adjusting the sludge age online to the requirement has many advantages. The sludge age affects the oxygen demand, which is expected to be reduced as the sludge age is shortened. At the same time, a shorter sludge age will also trend for a lower system alpha value, causing an increased air requirement to transfer oxygen. The reduction in alpha does not, however, compensate for the lower oxygen demand and the net effect of a shorter sludge age is a reduction in energy consumption. During the two periods evaluated at Hammarby Sjöstadsverk, measurement of the blower voltage and current indicated energy savings of close to 30 %. Although these energy savings were a combined result of several operational changes, including the reduction of DO set point, part of the reduction is a direct effect of the shorter sludge age used.

Another advantage of optimized sludge age with automatic control is the ability to handle wet weather flows as a result of increased clarifier capacity. An online calculation of the recommended sludge age also ensures that the operators always know the required sludge age and thus the current capacity and requirement of their system while delivering acceptable effluent quality.

An automatic control of the required sludge age based on nitrification rate also gives early warnings when the sludge age is not adequate to provide sufficient treatment. Control of the sludge age could suggestively be used together with effluent control such as ammonia feedback to ensure proper control of both aeration and sludge age to reach sufficient treatment while still minimizing energy consumption.

Calculating a required sludge age is only one of many benefits of automating the calculation of nitrification and denitrification rates with online instrumentation. In the design stage, rates calculated from a number of facilities can be compared to each other and used to identify the impact of different BOD to TKN ratios to determine appropriate rates when designing facilities. The rates could also aid in determining the required cycle structure for a specific flow and loading condition. Using denitrification rate calculations during the settle phase of an SBR process can help determine the denitrification capacity of the system and enable reduction of anoxic periods during the react phase for designs where the effluent limits are not as stringent.

For an operator, the rate calculation can be used as a health check for the system. Decreased rates might be used to confirm the inhibition from an industry dumping toxins to a facility. The rate calculation could also be used to predict the required volatile mass for a process and from there the required mixed liquor concentration in the basin. Additional control opportunities for automatic rate calculations are automatic adjustments of the aeration period duration or the DO set point.

CONCLUSIONS

In this study, online measurements have been used to calculate nitrification and denitrification rates in two wastewater treatment plants using the Sanitaire ICEAS continuous flow SBR process. The results show that calculated values of both nitrification and denitrification rates from online measurements match well with published data.

The calculated rates can be used as a health check of the process and give an early indication of rate depletion due to potential toxins or other inhibitors. The rates can also be used for automatic sludge age control by calculating a nitrifier growth rate to define a required sludge age for the system. The calculated sludge age can be provided to an operator as an indicator of the process requirement, or could be used directly to automatically control the sludge wasting process. The results from the pilot plant at Hammarby Sjöstadsverk demonstrate how calculating the required sludge age from a specific nitrifier grown rate for a system can help optimize the process and energy consumption. By adjusting the actual sludge age to the calculated requirement, the overall sludge age used was reduced by 50 % while still maintaining the same level of treatment. This illustrates how controlling a process from calculated nitrification and denitrification rates gives a large potential for process optimization and energy reduction.

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