BIOLOGICAL TREATMENT OF NITROGEN RICH INDUSTRIAL WASTEWATER IN SEQUENCED BATCH REACTORS

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Abstract: Wastewater containing high nitrogen compounds in the form of ammonia (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N) and organic bound nitrogen (N) could be harmful to aquatic life, causes depletion of dissolved oxygen and eutrophication in receiving water bodies, and additionally influences the sustainability of wastewater for reuse. Biological nitrogen removal technologies are generally used to expel nitrogen from wastewater, and secure natural water quality. A sequential batch reactor was designed capable of removing nitrogen from wastewater through pre-denitrification method. The study evaluated the important pre-denitrification design parameters as a function of anoxic sludge age. The wastewater is of poultry meat processing from a company called Taravis, located at Sárvár in Hungary. Samples were collected twice on different dates and the characteristics of the wastewater were measured and one of the measurement was doubled and termed theoretical maximum. The daily influent wastewater is 1000 m^3/day, three reactors are proposed to be used with a total cycle time of 12 hours and an anoxic sludge age of 13 days. Each reactor was sized as having a depth of 6.5 meters, 9.5 meters width and 9.5 meters length and a tank volume of 556 m^3. The nitrification capacities, N_{OX}'s were evaluated as 144 mg N/l, 68 mg N/l and 287 mg N/l for the first, second and theoretical maximum respectively while the denitrification potentials, N_{DP}'s were evaluated as 85 mg N/l, 79 mg N/l and 184 mg N/l for the first, second and theoretical maximum respectively. The result shows that the effluent to be discharge is within the acceptable Hungarian limit.

Keywords: Biological treatment, Design, Nitrogen, Sequential Batch reactor, Wastewater

Introduction

The increase of human populace requests new water resources and furthermore brings about increased amount of wastewater to be treated before being released into the natural ecosystems (Escapa *et al.*, 2015). Because of the limited water resources particularly in dry climatic regions, wastewater treatment and consequent reusing is a practical choice that can help tackle limited water resources problem (Ali & Okabe, 2015). The wastewater containing high nitrogen compounds in the form of ammonia (NH_4-N), nitrite (NO_2-N), nitrate (NO_3-N) and organic bound nitrogen (N) could be harmful to aquatic life, causes depletion of dissolved oxygen and eutrophication in receiving water bodies, and additionally influences the sustainability of wastewater for reuse (Zhao *et al.*, 2010). Both nitrification and denitrification have nitrite (NO_2^-) as an intermediate. Hence, if nitrification is halted at nitrite (nitritation), then complete denitritation from nitrite to nitrogen gas can be achieved. Nitrogen removal by means of nitrite may yield up to a 25% decrease in aeration and 40% lessening in chemical oxygen demand (COD) requirement (Peng *et al.*, 2006). The reduction in COD requirement would be especially profitable for wastewater treatment plants (WWTPs) treating wastewater insufficient in COD for the required nitrogen evacuation by means of nitrate (Lobo *et al.*, 2016). Sequencing Batch Reactor (SBR) practically includes five well characterized stages; fill, react, settle, draw and idle (Annesini *et al.*, 2014). These stages can be optimized for every specific case. The fundamental preferences of SBR in comparison with other biological treatment are high flexibility, simple running, firm layout, better control of stun loads, plausibility of accomplishing anoxic or anaerobic conditions in a similar tank and good oxygen contact with microorganisms and substrates (Lobo *et al.*, 2016). SBR design and operation are typically based on predetermined, timed cycles even though oxidation–reduction potential (ORP) and pH monitoring are gaining popularity as a means of optimizing aeration and overall treatment efficiency (Wareham *et al.*, 1993).

Methodology

Sample Preparation and Characterization

The wastewater samples used in this study were collected from a company called Taravis, located at Sárvár in Hungary. The samples arrived in a plastic container without preservatives and were stored at 4°C until measurement could be started. A fraction of the sample was filtered using vacuum filtration. The wastewater is of poultry meat processing and the samples were taken after flotation / physico-chemical treatment. As there are plans to build a facility to treat the technological wastewater of the company in situ, the aim of this thesis is to calculate the size of the plant that is capable of treatment to meet the quality requirements of discharging to natural surface water. Two point samples were collected at different times. The first measurement was conducted on April 11th, 2018 and the second measurement was done on April 19th, 2018 while the theoretical maximum was evaluated by doubling the result of the measurement with high wastewater characteristics (first measurement). Total nitrogen, Ammonium nitrogen, Nitrite nitrogen, Nitrate nitrogen, Total Phosphorus, ortho-phosphate, BOD_5, Total suspended solids, total dissolved solid and COD were analyzed according to standards methods (APHA, 2005).

Process Description

This chapter describes a unified design procedure for SBR systems operated for nitrogen removal. The design of nitrogen removing SBR systems is structured based upon nitrogen mass balances. This method is used to size the SBR tanks to achieve sufficient treatment of the poultry wastewater of Taravis Ltd.

The total reactor volume will includes a stationary volume, V_0 holding settled biomass and a fill volume, V_F which will be filled and discharged in each cycle. As reported by Artan et al., (2003), V_0/V_F ratio has the same function as the total recycle ratio in continuous-flow systems. In the fill phase, T_F, poultry wastewater will be fed into the reactor on the

settled biomass remaining from the previous cycle. Additional time will be allowed after fill, for the biological reactions to further progress during the react phase, T_R. Biomass will be left to settle in the settle phase, T_S. The treated wastewater volume will be discharge in the draw phase; T_D and the reactor will be left idle in the idle phase, T_I. The total cycle time, T_C, will be the sum of these phases. Biological processes will be assumed to take place only during the process phase; T_P corresponding to the sum of fill and react phases (Morgenroth & Wilderer, 1998).
As reported by Artan *et al.*, (2003), for nitrogen removal in SBR systems the process phase includes a mixed phase, T_M for denitrification and an aerated phase, T_A for nitrification.
Ketchun, (1997) reported that for organic carbon and suspended solids reduction, nitrification and denitrification is accomplished by increasing the time of the reaction phase to assure oxidation of the ammonia and that; the period of mixed react is introduced near the end of react and shortly before a short period of reaction phase. Mixed react provides for the removal of nitrates produced from ammonia nitrification at the end of aerated fill and during aerated react.

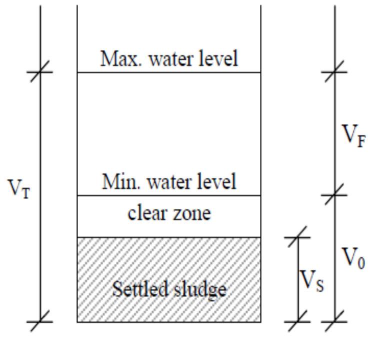

Fig. 1 Schematic representation of SBR (Orhon *et al.*, 2005)

Cycle Frequency (m)
Number of cycles per day, m, is an important parameter to be selected in SBR design and operation. Orhon *et al.*, (2005) defines the total cycle time, T_C and the fill volume per cycle, V_f as;

$$T_C = \frac{1}{m} \quad (1)$$

$$V_F = \frac{Q}{m} \quad (2)$$

Where Q is the daily volumetric flow rate of the wastewater
Nominal Hydraulic Retention Time (HRT)
Artan *et al.*, (2003) and Boursier *et al.*, (2005) reported that nominal hydraulic retention time, θh is usually defined for SBRs similar to continuous flow activated sludge systems as V_T /Q and can be as expressed a function of T_C;

$$\theta_h = \frac{V_T}{Q} = \frac{V_O+V_F}{m.V_F} = \left(1+\frac{V_O}{V_F}\right).T_C \quad (3)$$

θ_h Can also be expressed in terms of the volumetric exchange ratio, V_{ER}, which is defined as the ratio of the fill volume to the total volume.

$$\theta_h = \frac{V_T}{mV_F} = \frac{T_C}{V_{ER}} \quad (4)$$

The total cycle time, T_C can be defined as;

$$T_C = T_P + T_{S+D+I} \quad (5)$$

The duration of fill time, T_F, can range from a small fraction of total cycle time to total process time, or even to the total cycle time and fill time ratio, FTR, is defined as

$$FTR = \frac{T_F}{T_C} \quad (6)$$

Duration of Periods in a Process Phase
The process phase can be fully aerobic as in the systems for COD removal or can have various environmental conditions adjusted by energy input. In nutrient removal SBR systems, the process phase T_P consists of aerated periods, (T_A), and mixed periods, (T_M), which can be anoxic or anaerobic depending on the presence of nitrate (Orhon *et al.*, 2005 and Orhon *et al.*, 1997).

$$T_P = T_M + T_A = T_{AN} + T_{AOX} + T_A \quad (7)$$

Number of Tanks
Artan *et al.*, (2003); Boursier *et al.*, (2005); Gao *et al.*, (2010); Ketchum, (1997) and Orhon *et al.*, (2005) reported that SBR process can be carried out in a single reactor or in multiple reactors in parallel. If equalization is not used, a continuous wastewater flow can be accommodated by providing multiple reactors; for n reactors, the equation below applies;

$$T_C = n.T_F \quad (8)$$

Thus,

$$FTR = \frac{1}{n} \quad (9)$$

Sludge Retention Time (SRT)
The sludge retention time (SRT) for SBR system, Θ_X, is defined as the mass of sludge contained in the reactor, M_{XT}, divided by the sludge wasted per day, P_{XT}, as for the continuous-flow systems

$$\theta_X = \frac{M_{XT}}{P_{XT}} \quad (10)$$

Sludge wasting from the mixed liquor may provide a simple and direct means of controlling θ_X. In this case, θ_X may be defined, as follows, in terms of the total reactor volume, V_T, the volume of the sludge wasted from mixed liquor each cycle, V_W, and the cycle time, T_C. In practice however, excess sludge wasting takes place mostly after settle phase on a daily or even weekly basis (Artan *et al.*, 2003; Boursier *et al.*, 2005; Gao *et al.*, 2010; Ketchum, 1997; Morgenroth, & Wilderer, 1998 and Orhon *et al.*, 2005).

$$\theta_X = \frac{V_T.X_T}{m.V_W.X_T} = \frac{V_T}{V_W}.T_C \quad (11)$$

The aerobic sludge age, Θ_{XA}, is defined as a function of the total aerated periods within the cycle, the only period of the operating cycle sustaining autotrophic growth.

$$\theta_{XA} = \theta_X.\frac{T_A}{T_C} \quad (12)$$

Orhon *et al.*, (2005) and Lemaire *et al.*, (2008) stated that heterotrophic growth can take place during both the aerobic and anoxic periods. Growth and endogenous respiration processes are assumed to cease during the anaerobic period.
Hence, the effective period, T_E, is the sum of the aerobic, T_A, and anoxic, T_{AOX}, periods in nutrient removal systems while it is totally aerobic in carbon removal and nitrification systems. Thus, effective sludge retention time for heterotrophs is defined by (Artan *et al.*, 2003; Morgenroth, & Wilderer, 1998; Lemaire *et al.*, 2008; and Orhon *et al.*, 2005) as;

$$\theta_{XE} = \theta_X\frac{T_E}{T_C} = \theta_X\frac{T_A+T_{AOX}}{T_C} \quad (13)$$

The relationship between aerobic and effective sludge retention times can be expressed as below using above equations:

$$\theta_{XE} = \frac{\theta_{XA}}{(1+T_{AOX}/T_E)} \quad (14)$$

$$S_p = F_{SE}b_H\frac{Y_H}{(1+b_H\theta_{XE})}C_{SI}\theta_X \quad (15)$$

Where F_{SE} is the soluble inert fraction of endogenous decay.

$$Y_{NH} = (1+F_Eb_H\theta_{XE})\frac{Y_H}{1+b_H\theta_{XE}} \quad (16)$$

Where F_E is the inert fraction of biomass.
Equation 15 and 16 are used in determining the effluent COD and net heterotrophic coefficient respectively.
Nitrogen Balance
Artan *et al.*, (2003), Orhon *et al.*, (1997) and Orhon *et al.*, (2005), shows that nitrogen removal in SBRs, as in all

biological systems, depends upon the balance between nitrification capacity, N_{OX}, denitrification potential, N_{DP}, and available nitrate N_A, corresponding to the nitrate concentration or the magnitude of oxidized nitrogen supplied to the mixed periods. NO_X is calculated from the mass balance for TKN:

$$N_{OX} = C_{TKNI} - N_X - S_{NH} - i_{NSI}S_{ii} - i_{NXI.}X_{ii} \quad (17)$$

Where C_{TKNI} is influent total Kjeldahl nitrogen, mg N/l; S_{TKN} is effluent soluble inert organic nitrogen and N_X is the concentration of nitrogen that is incorporated into biomass and removed from the system as part of excess sludge. In this expression, the non-biodegradable nitrogen components, by-passing biological conversion are defined as fractions (i_{NSI}; i_{NXI}) of their soluble and particulate COD counterparts in the wastewater, S_{ii} and X_{ii}. The effluent ammonia nitrogen concentration, S_{NH} is a function the aerobic SRT. The net heterotrophic yield coefficient, Y_{NH}, which is the function of θ_{XE}, determines N_X. Calculation of N_X requires the assessment of nitrogen content of biomass, i_{NBM}:

$$N_X = i_{NBM}Y_{NH}C_{S1} \quad (18)$$

The denitrification potential, N_{DP} indicates the concentration of nitrate nitrogen that may be potentially removed, provided that enough nitrate nitrogen is supplied to the non-aerated period. It can be defined as a fraction of the nitrate nitrogen equivalent of the total electron acceptor demand associated with the heterotrophic growth on both readily biodegradable substrate, N_{SS}, and slowly biodegradable substrate, N_{XS}, and endogenous respiration, N_{ER}. The expressions assume that all biodegradable COD is consumed for the selected effective SRT:

Denitrification potential due to endogenous respiration depends linearly on the mixed period fraction, T_M/T_P, since the endogenous respiration rate is approximately constant.

$$N_{SS} = (1-Y_H)\frac{S_{Si}}{2.86} \quad (19)$$

$$N_{XS} = \eta(1-Y_H)\frac{X_{Si}}{2.86} \quad (20)$$

$$N_{ER} = \eta\,(1-f_{XE})\,b_H\Theta_{XE}\,\frac{YH}{1+bH\Theta XE}\,\frac{S_{Si}+X_{Si}}{2.86} \quad (21)$$

$$N_{DP} = N_{SS} + \frac{TM}{Tp}(N_{XS} + N_{ER}) \quad (22)$$

Denitrification efficiency, E, will be determined by NDP provided that enough nitrate is supplied during the mixed period.

$$E = \frac{N_{Dp}}{N_{OX}} \quad \text{if NA >=NDP} \quad (23)$$

Effluent nitrate is determined using the equation below;

$$S_{NO} = \frac{N_{OX}}{1+{}^{Vo}/_{V_F}} \quad (24)$$

Total oxygen required is evaluated by;

$$O_{RT} = (1 - Y_{NH})C_{SI} + (4.57 - Y_{NA})N_{OX} - 2.86\,(N_{OX} - S_{NO}) \quad (25)$$

Sludge production is calculated using;

$$P_{XT} = i_{TSS,COD}\,(Y_{NH}C_{SI} + Y_{NA}N_{OX} + X_{ii}) + XF_{si} \quad (26)$$

$$S_{NH} = \frac{K_{NH}(1+b_A\theta_{XA})}{U_{AMAX}\theta_{XA}-(1+b_A\theta_{XA})} \quad (27)$$

Result and Discussion

A design exercise for nitrogen removal by means of pre-denitrification is provided in this section based on the information retrieved from Taravis Ltd regarding the capacity of the wastewater generated in the technology and three set of data regarding the quality of their wastewater. Table 1 shows the daily wastewater flow rate, average load, peak load and pH range of the Taravis treatment plant, located at Sárvár in Hungary. The daily flow rate here was used as the basis of the SBR pre-denitrification system design.

Table 1: Design Parameters

Parameter	Basic Design Data
Flow rate (Q)	1000 m^3/d
Average load	42 m^3/h
Peak Load	100 m^3/h
pH	6.5-9.0

Table 2: Measured Wastewater Characteristics

Parameter	First Measurement	Second Measurement	Theoretical Maximum
COD (mg COD/l)	1122	960	2244
Dissolved COD (mg COD/l)	846	590	1692
BOD_5 (mg O_2/l)	374	512	748
pH	6.3	7.2	6.3
NH_4-N (mg NH_4-N/l)	48	11.4	96
NO_2-N (mg NO_2-N/l)	0.01	0.01	0.02
NO_3-N (mg NO_3-N/l)	0.91	0.73	1.64
TKN (mg N/l)	167	89	334
Total Nitrogen (mg N/l)	168	90	336
TSS (mg TSS/l)	1861	1241	3722
TDS (mg TDS/l)	1727	1184	3454
Total Phosphorus (mg P/l)	2.19	3.99	4.38
Ortho-Phosphate (mg P/l)	1.17	0.41	2.34

Table 2 shows the wastewater characteristics, and from the wastewater characteristics, it can be seen that the ratio of the organic N and total TKN is high enough to the COD which requires nitrification/denitrification and also, it can be seen that these wastewater is a nitrogen rich wastewater. The result of the first measurement has a higher TKN with a lower COD/TKN ratio of 6.72 as compared to the second measurement which has a lower TKN and a higher COD/TKN ratio of 10.79. TSS is higher than the COD that means that there is quite a lot of inorganic matter in the wastewater. The suspended COD (Total- dissolved) is significantly less than TSS, underlining the previous assumption. The BOD/COD ratio is quite bad for the first case 33%, the second case is better. This suggest the lack of easily degradable organic materials. So even though the nitrogen concentration is relatively low, even comparable to Selected periods for the SBR processes and the calculated fill time, based on the selected periods. All calculated data in this work is done on the designed spreadsheet are presented in table 3 and 5 below using the kinetic coefficients and constant given in Table 4. The values are considered as the final after doing a few steps of iteration to determine the optimum designed parameters.

Table 3: Process Cycle times and the tank dimensions

Process	Data
Aeration Time, T_A (hr)	2
Anoxic time, T_{AN} (hr)	1
Settling Time, T_S (hr)	2
Decant time, T_D (hr)	1.5
Idle Time, T_I (hr)	1.5
Aerated fraction of Fill time (hr)	0.5
Sludge blanket depth,	1.2
Number of tanks, N	3
Fill Time, T_F (hr)	4
Number of cycles/day, N_C	6
Fill Volume/cycle, V_C (m^3/cycle)	167
Number of cycles/tank/day	2
Length/width ratio, L/W	1
Tank Freeboard (m)	0.3
Tank Liquid Volume, V_T (m^3/tank)	556
Tank Depth, D tank (m)	6.5
Tank Width, W (m)	9.5
Tank Length, L (m)	9.5
Anoxic sludge age, θ_{XA} (days)	13

Table 4: Kinetic coefficient and constant (Peng *et al.*, 2004**)**

	Value	Units
Half saturation coefficient, K_{NH}	1	mg N/l
Autotrophic endogenous decay coefficient, b_A	0.05	1/day
Maximum autotrophic growth rate, μ_{Amax}	0.25	1/day
Inert fraction of biomass, F_E	0.2	-
Heterotrophic yield coefficient, Y_H	0.64	mg cell COD/mg COD
Endogenous respiration rate coefficient, b_H	0.15	1/day
Autotrophic yield coefficient, Y_A	0.24	mg cell COD / mg N
Nitrogen content of inert particulate COD, i_{NXI}	0.05	mg N/mg COD
Nitrogen content of inert soluble COD, i_{NSI}	0.03	mg N/mg COD
Nitrogen content of biomass, i_{NBM}	0.085	mg N/mg COD
Coefficient to convert COD to TSS, i_{TSSCOD}	0.9	mg TSS/mg COD
Readily biodegradable fraction, F_{SS}	0.2	-
Anoxic correction factor, η	0.8	-
Safety factor, SF	1.3	-

Table 5: Calculated design parameters for the measurement

Design Parameter	Symbol	Unit	First measurement	Second Measurement	Theoretical Maximum
Aerobic sludge age	θ_{XA}	day	13	13	13
Effluent ammonium nitrogen	S_{NH}	mg N/l	1.03	1.03	1.03
Anoxic sludge fraction	T_{AOX}/T_E	-	0.33	0.33	0.33
Effective sludge age	θ_{XE}	day	20	20	20
Hydraulic retention time	θ_h	hr	40	37	73
Sludge age	θ_X	day	28	28	28
Cycle time	T_C	hr	12	12	12
Net heterotrophic yield	Y_{NH}	mg COD/ mg COD	0.258	0.258	0.258
Net Autotrophic yield	Y_{NA}	mg COD/ mg N	0.145	0.145	0.145
Nitrogen in biomass	N_X	mg N/l	19	18	42
Nitrification capacity	N_{OX}	mg N/l	144	68	287
Denitrification potential	N_{DP}	mg N/l	85	79	184
Required available nitrate	N_A	mg N/l	102	46	239
Required recycle ratio	V_O/V_F	-	2.37	2.10	4.74
Effluent nitrate nitrogen	S_{NO}	mg N/l	43	22	47
Sludge production	P_{XT}	mg TSS/l	234	207	501
Total oxygen requirement	O_{RT}	kg O2/d	1005	775	1998
Aerator power required,	P	kW	64	49.64	128
Denitrification efficiency	E	%	70	68	84

A sludge age θ_{XA} of 13 days was selected as the best after doing iterations and an effluent ammonia concentrations, S_{NH} for the first sample, second sample and theoretical maximum were computed using equation 27 as 1.03 mg/l, for the wastewater samples. As the adopted value for $S_{NH,\ D}$ is 2.0 mg/l (Orhon *et al.*, 2005), $S_{NH} < S_{NH,\ D}$ condition is safely satisfied and confirms that θ_{XA} selection is acceptable. A T_{AOX}/T_E value of 0.33 is estimated by iteration, this value yields an effective sludge age, θ_{XE} of 20 days using equation 14 and enables to calculate the net heterotrophic yield, Y_{NH} as 0.258 mg COD/mg COD using equation 16 which determines the concentration of nitrogen to be incorporated into biomass and removed from the system as part of excess sludge, N_X as 19 mg N/l, 18 mg N/l, and 48 mg N/l for first sample, second sample and theoretical maximum respectively using equation 18. With this information, the nitrification capacity, N_{OX} and the denitrification potential, N_{DP} for the first sample, second sample and theoretical maximum were then computed using equations 17 & 22 as 144 mg N/l, 68 mg N/ l, & 287 mg N/l and 85 mg N/l, 79 mg N/l, & 184 mg N/l respectively. The system performance of first sample, second sample and theoretical maximum however, can only be achieved if a minimum of 102 mg N/l, 46 mg N/l & 239 mg N/l of nitrate is recycled into the anoxic phase respectively. A recycle ratios calculated V_O/V_F satisfied the 2.37, 2.10 & 4.74 < 4-5 condition which provides the necessary N_A to be denitrified during the anoxic phase.

Table 6: Comparison of effluent limit and calculated results

Parameters	Hungarian effluent Limits	Effluents		
		1st Measurement	2nd Measurement	Theoretical Maximum
COD mg COD/l	150	41.71	38.46	89.9
Inorganic Nitrogen mg N/l	50	44	23	48
TSS mg TSS/l	200	62.49	70.60	57.89
TP mg P/l	10	0	1.92	0.27
NH_4-N	20	1.03	1.03	1.03

As reported by Peng *et al.,* (2006), if nitritation is to be considered, there will be 25% decrease in aeration which implies that equation 25 will becomes;

$$O_{RT} = (1 - Y_{NH})C_{SI} + (3.43 - Y_{NA})N_{OX} - 1.71(N_{OX} - S_{NO}) \quad (28)$$

And based on this equation we will have total oxygen requirement of 956.9 kg O_2/d, 749.9 kgO_2/d and 1946.3 kg O_2/d for the first measurement, second measurement and theoretical maximum respectively. This means 25-51 kg O_2/d saving if we consider the new numbers. The N-removal via nitrite actually saves organic matter which can be good in case of low COD/TKN ratio.

From Table 6, it can be seen that according to the Hungarian waste water effluent standard (decree 28/2004) for all the parameters are within the acceptable limit.

Conclusion

The design findings show that choosing an optimum anoxic sludge age and anoxic sludge fraction yield excellent design parameters. Overall, this study demonstrated that it was possible to achieve consistent and acceptable wastewater effluent quality by treating a variable-composition wastewater with SBRs by pre-denitrification. Sizing of each of the reactor, and the design parameters such as nitrification potential, heterotrophic yield coefficient, available nitrate and denitrification potential was done in order to achieve the goal.

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