

The Effect of Ammonia Loading on the Nitrification Kinetic of Aerobic Baffled Continuous Biological Reactor

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Abstract - The purpose of this study is to determine the degradation rate of ammonia in the modified activated-sludge system through a modified, laboratory scale biological reactor. To achieve this, a modified biological reactor with pre-installed continuous narrow baffle walls operating at extended aeration (SRT = 40 days) was designed to intentionally create a number of complete-mix activated-sludge zones. In order to compare the performance, a control reactor (SRT = 2 days) operating at conventional aeration was created to simulate the conventional activated-sludge process in the domestic STP. After the acclimatization period, the influent ammonia was increased gradually by approximately 15 mg/L and the corresponding effluent ammonia level was monitored. Based on the analysis, the nitrification kinetic of the control and modified reactor was observed to be 0.0823 and 10.321, respectively. The nitrification kinetic of the control reactor was considered as negligible due to the conventional activated-sludge process, which inhibits the growth of nitrifiers. In contrast, the modified reactor has achieved nitrification kinetic of 10.32, due to the narrow baffle walls that increased the overall retention time.

Index Terms - ammonia-nitrogen, solid retention time, modified conventional activated-sludge, baffled reactor

I. INTRODUCTION

Ammonia-nitrogen (NH_3) is a constituent in raw domestic wastewater. However, the degradation of the organic matter in the biological treatment stage also produce substantial amount of ammonia compounds. Through the biological nitrification process, ammonia (NH_3) is oxidized to nitrite (NO_2^-), and nitrate (NO_3^-), by aerobic autotrophic bacteria. The final output of nitrification process, which is nitrate (NO_3^-) could be reduced to nitrogen gas (N_2) through de-nitrification process under anoxic condition^[1].

The sewage discharge from the domestic sewage treatment plant is typically subjected to the local, state and federal regulations and standards. In December 2009, the Department of Environment (D.O.E) Malaysia has revised the *Environmental Quality (Sewage) Regulations 2009*, which significantly reduced the discharge limit of ammonia-nitrogen (NH_3) from 50 mg/L to 5 mg/L. In addition, a new discharge limit was also set for nitrate at 10 mg/L^[2].

The solids retention time (SRT) is the most important design and operating parameter for the activated sludge

process as it represents the average period of time the biomass remains in the system before wasted. SRT affects the treatment process performance, aeration tank volume, sludge production, and oxygen requirements^[1]. The minimum sludge age required to achieve 100% of nitrification is shown to be 16 days through experimental work^[3]. Typical design SRT values may range from 10 to 20 days at 10°C to 4 to 7 days at 20°C. Above 28°C, both ammonia and nitrite oxidation kinetics should be considered^[4]. However, for complete nitrification to take place and to stabilize the sludge, the sludge age recommended for extended aeration should range from 20 to 40 days^[1].

Nitrification is affected by a number of environmental factors including pH, toxicity, metals, and un-ionized ammonia. Nitrification is pH-sensitive and rates decline significantly at pH values below 6.8. At pH values near 5.8 to 6.0, the rates may be 10 to 20 percent of the rate at pH 7.0. It was proven that optimal nitrification rates occur at pH values in the 7.5 to 8.0 range, therefore a pH of 7.0 to 7.2 is normally used to maintain reasonably nitrification rates^[5]. On the other hand, nitrifying organisms are sensitive to a wide range of organic and inorganic compounds; nitrifiers have been shown to be good indicators of the presence of organic toxic compounds at low concentrations^[6].

Activated-sludge processes can be designed with baffle walls to intentionally create a number of complete-mix activated-sludge zones operating in series. For the same reactor volume, reactors in series can provide greater treatment capacity. Modified Ludzak-Ettinger (MLE) process is the most common process used for biological nitrogen removal in municipal wastewater treatment. The process consists of an anoxic tank followed by the aeration tank where nitrification occurs. Nitrate produced in the aeration tank is recycled back to the anoxic tank. Because the organic substrate in the influent wastewater provides the electron donor for oxidation reduction reactions using nitrate, the process is termed substrate denitrification. Further, because of the anoxic process precedes the aeration tank, the process is known as a preanoxic denitrification^[1].

II. KINETICS RELATIONSHIP FOR CONTINUOUS BIOLOGICAL REACTOR

It is often desirable to portray the activated-sludge process by mathematical model and then to evaluate with the experimental data obtained by utilizing a series of bench-scale laboratory reactors. Study of the kinetics of aerobic biological treatment yields the rate at which the microorganism degrade a specific parameter, and therefore provides the basic information required for sizing biological aerobic reactors^[8].

There are two fundamental differences between the

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operation of continuous and batch reactors. Contrary to what happens in the batch reactor, the substrate (BOD) of the wastewater in the continuous reactor operating at steady-state conditions remains constant. This corresponds generally to a low substrate concentration since the biological reactor is usually designed for removing most of the influent BOD. On the other hand, concentration of MLVSS in the continuous reactor operating at steady-state is kept constant at a selected value. Maintenance of this constant is obtained by providing the calculated amount of concentrated return sludge [8].

In a continuous biological reactor operating under steady-state (assuming substrate concentration remains constant) and complete-mix conditions, the substrate entering and leaving the reactor is in a state of equilibrium [8]. The specific substrate removal rate corresponds to the rate of removal of substrate in the continuous reactor per unit mass of MLVSS present in the reactor. Assuming the substrate removal follows first-order kinetics, through mathematical manipulation of equations, the final equation indicates that the specific substrate removal rate is proportional to substrate concentration (first-order kinetics). Substrate removal rate constant k can be obtained from a plot of specific substrate removal rate versus substrate concentration as presented in figure 1:

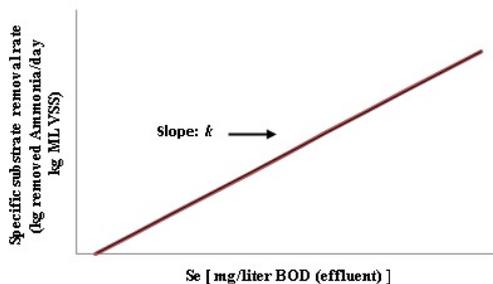


Fig. 1. Graphical determination of kinetic, k

The graph shown in figure 1 indicates a straight line, assuming applicability of the mathematical model. Whenever BOD is utilized as a measure of the substrate concentration, the graph will yield a straight line passing through the origin; this corresponds to complete removal of substrate. However, if some other parameters (e.g. COD, Ammonia) are utilized to measure substrate concentration, the straight line may not pass through the origin [8].

III. METHODOLOGY

The principle conceptual design was to simulate complete-mix activated-sludge process in the modified reactor. The optimum aeration volume for single-sludge (BOD removal and nitrification) process was determined from the process design calculation, based on the assumed organic loading $0.0016 \text{ kg BOD}_5/\text{day}$ and mixed-liquor temperature 20°C . A series of continuous narrow baffle walls was installed to intentionally create a number of complete-mix activated-sludge zones (figure 2). The gap between each baffle wall was designed to be 10 mm, in order to induce the plug-flow of the sludge through hydraulic and gravity action, keeping the biomass in complete suspension. Based on the design calculation, the baffle walls were configured to occupy a total volume of 8.5 liters with 20

partitions (HRT = 26 hours). Two liters of anoxic compartment was provided prior to the aeration chamber (HRT = 2 hours). The supernatant in the clarifier were recycled back to the pre-anoxic compartment for de-nitrification. A similar reactor without the baffle walls was created to simulate the conventional aeration basin.

Next, synthetic wastewater was produced by dissolving grinded cats' food in distilled water to imitate medium strength domestic wastewater, mainly to provide more consistent organic loadings. Different concentrations of synthetic wastewater were evaluated in the laboratory to find the suitable concentration and sufficient nutrients (C: N: P ratio) for the microorganisms.

The designed reactors were fabricated with 5 mm thick acrylic glass, and a sufficient number of tube diffusers were installed to ensure minimum D.O. of 2 mg/L. During the operation stage, both of the reactors were set up in the laboratory by using biological biomass from the domestic STP as the starting biomass. Influent was pumped into the reactors continuously at the rate of 8 liters/day by using Masterflex Precision Pump with tubing L/S 16 (figure 4). The modified reactor was operated at extended aeration (SRT = 40 days, design MLSS = 3000 mg/L), while the control reactor (figure 3) was operated at conventional aeration (SRT = 2 days, design MLSS = 1000 mg/L). 10 days of acclimatization period was set to stabilize the biomass, and the sludge age was controlled through daily sludge recycling and wasting. Influent and effluent samples were collected daily at a pre-determined time and the performance of both reactors was monitored continuously until the readings were stabilized. Subsequently, the concentration of ammonia was increased by approximately 15 mg/L every 4 days by adding in ammonium chloride. 50 mg/L of ammonium chloride will create approximately 15 mg/L of ammonia loading in the influent.

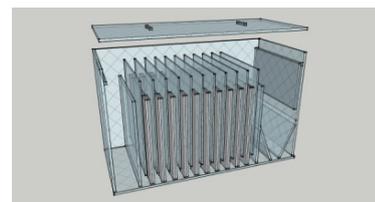


Fig. 2. Computer simulation of the modified reactor

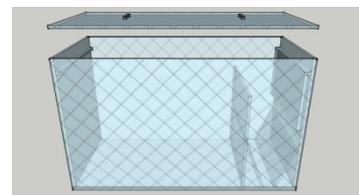


Fig. 3. Computer simulation of the control reactor



Fig. 4. Laboratory reactors

IV. CHARACTERISTICS STUDY OF SYNTHETIC WASTEWATER

The characteristics of cats' food were examined to determine its feasibility as the synthetic wastewater. 0.5 gram of grinded cats food dissolved in 1 liter of distilled water produced the following parameters:

TABLE I: CHARACTERISTICS OF 0.5 GRAM/LITER OF DISSOLVED CATS' FOOD

Parameter	Value (mg/L)
COD	450
BOD ₅	200
TSS	180
TKN	70
NH ₃	14
NO ₃ ⁻	Negligible
Phosphorus	8
C:N:P	100:16:2

0.5 gram/liters of dissolved cats' food was found to exhibit the characteristics of medium strength domestic wastewater. The minimum C: N: P ratio was studied to ensure there are sufficient nutrients for the microorganisms. The concentration of ammonia in the synthetic wastewater was noticed to be lower compared to typical domestic wastewater. Nevertheless, ammonia is produced during the hydrolysis of protein in the biological treatment stage, therefore contributing to the overall ammonia content.

V. REMOVAL OF ORGANIC MATTERS (COD & BOD₅) AND TOTAL SUSPENDED SOLIDS (TSS)

The performance of the activated-sludge processes in removing organic matters was measured in terms of COD and BOD₅ values. Throughout 10 days of monitoring period, the average COD and BOD₅ in the influent were found to be 445 mg/L and 210 mg/L, respectively. This tallied with the characteristics study of the synthetic wastewater. By comparison, the modified reactor effectively removed 92.3% of COD and 91.7% of BOD₅ in average, while the control reactor managed to remove 87.7% of COD and 87.0% of BOD₅. This indicates that the modified reactor slightly outperformed the control reactor in the removal of organic matters. Nevertheless, the average value of COD and BOD₅ in the effluent discharge from both of the reactors was shown to meet the D.O.E regulations (figure 5 and 6).

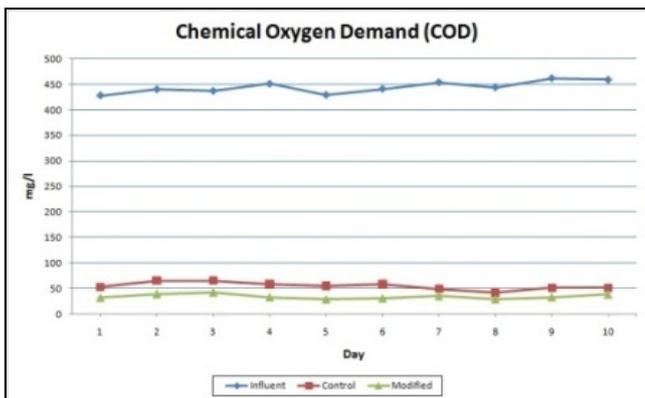


Fig. 5. Readings of COD

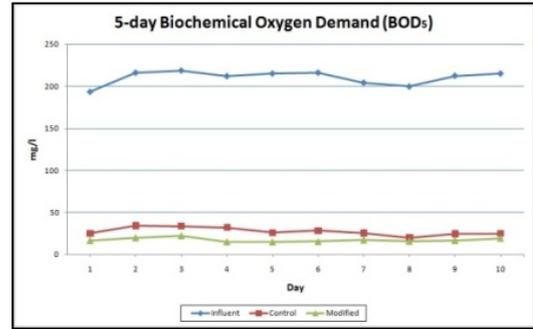


Fig. 6. Readings of BOD₅

The total suspended solids (TSS) is one of the most important physical characteristic of wastewater, as wastewater contains a variety of solid materials varying from rags to colloidal material. On average, the TSS level in the influent was found to be 191 mg/L, while the TSS in the effluents for both control and modified reactor was observed to be ranging from 43 to 46 mg/L (figure 7):

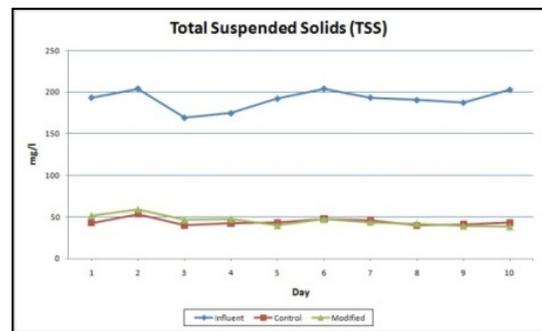


Fig. 7. Readings of TSS

VI. REMOVAL OF AMMONIA-NITROGEN AND NITRATE

The main parameter of concern in this study is ammonia-nitrogen (NH₃), which forms the basis for the design of the modified reactor. In order to encourage nitrification, the modified reactor was operated at extended aeration to provide higher retention time for the nitrifiers to grow. Figure 8 shows the average ammonia level in the influent to be 14 mg/L. By comparison, the modified reactor has effectively removed about 97.5% of ammonia in average, while the control reactor only managed to remove approximately 35.8% of ammonia. This has proven that the modified reactor has significantly outperformed the control reactor by approximately 60% in the ammonia removal capacity. Furthermore, the average ammonia level in the effluent discharge from the control reactor was noticed to violate the regulations limit, which averaged 9.1 mg/L.

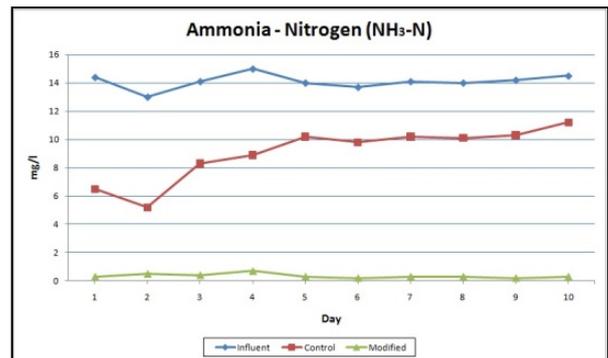


Fig. 8. Readings of Ammonia-Nitrogen

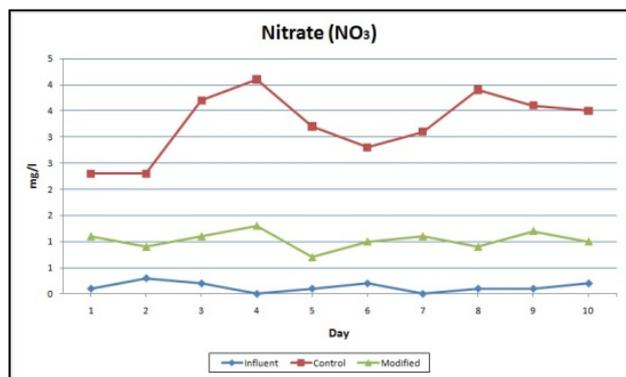


Fig. 9. Readings of Nitrate

Due to the pre-anoxic compartment in the modified reactor, the average nitrate level in the modified reactor was observed to be approximately 1.0 mg/L. A certain level of nitrate was found in the effluent of the control reactor, ranging from 2.3 to 4.1 mg/L, which indicate low nitrification rate in the control reactor.

VII. MONITORING OF MLVSS, SVI, PH AND TEMPERATURE

The amount of the microorganisms in the biological sludge is denoted by the mixed-liquor volatile suspended-solids (MLVSS), and it is an important design criterion in the activated-sludge process. At steady state, the concentration of biological biomass in the reactors remained approximately constant. Owing to the synthesis of the biological matter, there is a net yield of MLVSS in the reactor; therefore it is necessary to remove from the system a mass of MLVSS daily to maintain the required concentration. On average, the MLVSS value for control and modified reactors were determined to be 1062 mg/L and 2056 mg/L, respectively. No significant exponential biomass growth was observed for both of the reactors during the first 10 days of performance monitoring process. The SVI values for both reactors are ranging from 43 to 55, showing a good settling characteristic (SVI < 100). The average pH was maintained at 7.3 for the influent sample, and ranging between 7.7 to 7.8 for the effluents. On the other hand, the temperature of the influent was close to room temperature at 25 °C, while the temperatures for both effluents were measured to be around 21 °C due to aeration process. Table 2 shows the average value of the measured parameters:

TABLE 2: AVERAGE VALUE OF MEASURED PARAMETER

Parameter	Influent	Control	Modified
MLSS	-	1829 mg/L	3478 mg/L
MLVSS	-	1062 mg/L	2056 mg/L
SVI	-	55	43
pH	7.3	7.7	7.8
Temperature	25.2	21.5	21.8

VIII. NITRIFICATION KINETICS, K, FOR CONTINUOUS BIOLOGICAL REACTOR

After the biomass acclimatized to the substrate, the ammonia concentration in the influent was increased gradually by adding in ammonium chloride. 50 mg/L of

ammonium chloride was added into the influent to raise the ammonia concentration by approximately 15 mg/L, and the ammonia concentration was doubled every 4 days, in order to compare the nitrification kinetics between the control and the modified reactor. The corresponding effluent ammonia level was monitored along with the biomass concentration (MLVSS), as shown in table 3.

TABLE 3: VARIATION OF INFLUENT AMMONIA LEVEL AND THE CORRESPONDING EFFLUENT AMMONIA

Day	Conc. of NH_4Cl (mg/L)	Ammonia-Nitrogen (NH_3-N)		
		Influent	Effluent (mg/L)	
		Control	Control	Modified
1	0	13.7	5.5	0.1
2		14.1	5.9	0.3
3		14.0	5.8	0.2
4		14.3	6.2	0.3
5	50	27.3	10.2	0.7
6		28.8	9.9	0.9
7		28.3	10.6	0.7
8		27.9	10.8	0.8
9	100	41.2	16.3	1.1
10		42.3	16.0	1.3
11		41.9	15.9	1.2
12		41.9	16.2	1.3

From the results, the specific substrate removal rate (kg ammonia removed per day / kg MLVSS) was calculated for both reactors, as shown in table 4.

TABLE 4: KG OF AMMONIA-NITROGEN REMOVED PER DAY

Kg of Ammonia-Nitrogen (NH_3-N) removed per day			
Kg NH_3 - Removed/d		MLVSS (Kg)	
Control	Modified	Control	Modified
0.00006560	0.00010880	0.0009290	0.0020310
0.00006560	0.00011040	0.0007797	0.0020253
0.00006560	0.00011040	0.0006523	0.0020550
0.00006480	0.00011200	0.0005570	0.0020610
0.00013680	0.00021280	0.0005673	0.0020330
0.00015120	0.00022320	0.0004477	0.0020810
0.00014160	0.00022080	0.0002290	0.0021807
0.00013680	0.00021680	0.0002243	0.0020930
0.00019920	0.00032080	0.0002123	0.0021113
0.00021040	0.00032800	0.0002217	0.0020980
0.00020800	0.00032560	0.0002190	0.0021813
0.00020560	0.00032480	0.0002270	0.0022177

Based on the data, the average specific substrate removal rate for a preset ammonia level was plotted against the average effluent ammonia to determine the slope of the graph, which corresponded to the nitrification kinetics (k) of the reactor. The nitrification kinetic yields the degradation rate of ammonia to nitrate, which indirectly indicating the growth

rate of nitrifiers. From figure 10 and 11, the nitrification kinetic of the control and modified reactor was observed to be 0.0823 and 10.321, respectively. The nitrification kinetic in the control reactor was considered as negligible due to the conventional activated-sludge process, which inhibits the growth of nitrifiers. In contrast, the modified reactor has achieved nitrification kinetic of 10.32, indicating a high degradation rate of ammonia-nitrogen, due to the continuous baffle walls that help to increase the overall retention time.

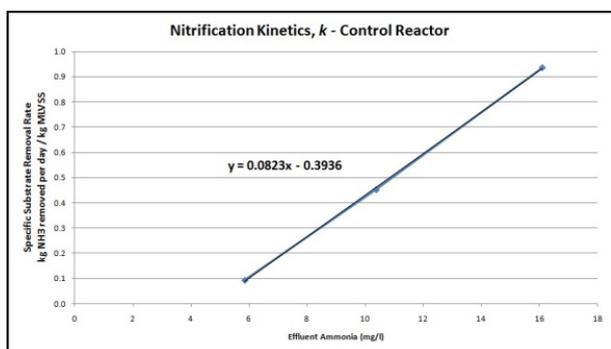


Fig. 10. Nitrification kinetics of conventional aeration

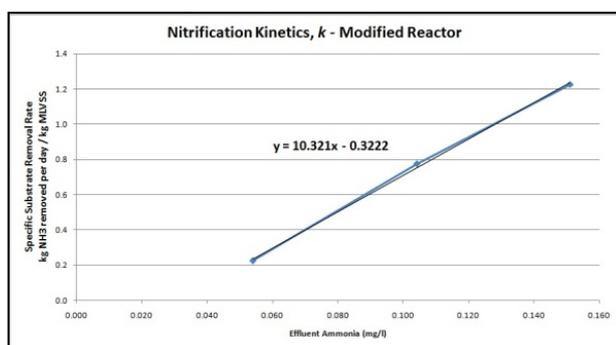


Fig. 11. Nitrification kinetics of extended aeration

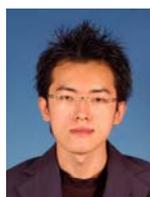
IX. CONCLUSION

The main purpose of this study is to determine the impacts of continuous narrow baffle walls to the nitrification kinetics of continuous biological reactor. Research has shown that for the same reactor volume, reactor in series can provide greater treatment capacity. Study of kinetics of aerobic biological

treatment yields the rate at which microorganisms degrade a specific waste, and therefore provides the basic information required for sizing of aeration chamber. Through a modified laboratory-scale biological reactor, the nitrification kinetics was determined to be 10.32, compared to 0.08 in conventional aeration. The results indicate that the continuous narrow baffle walls helps to increase the overall retention time and indirectly accelerate the nitrification process.

REFERENCES

- [1] Metcalf and Eddy, (2004). *Wastewater Engineering Treatment and Reuse*, Fourth Edition, McGraw-Hill, New York, USA.
- [2] Department of Environment Malaysia, (2009). *Environmental Quality (Sewage) Regulations 2009*, Environmental Quality Act 1974, Environmental Quality (Control of Pollution from Solid Waste Transfer Station and Landfill) Regulations 2009
- [3] Balakrishnan, S., & Eckenfelder W. W., (1970). *Nitrogen Removal by Modified Activated Sludge Process*, Journal of the Sanitary Engineering Division, Proceedings of the American Society of Civil Engineers.
- [4] Randall, C.W., Barnard, J. L., & Stensel, H. D., (1992). *Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal*, Volume 5, Water Quality Management Library, Technomic Publishing Co., Lancaster, PA.
- [5] United States Environmental Protection Agency, (1993). *U.S. EPA 1993*
- [6] Blum, D. J. W., & Speece, R. E., (1991). *A Database of Chemical Toxicity to Environmental Bacteria and Its use in Interspecies Comparisons and Correlations*, Research Journal, Water Pollution Control Federation, vol. 63, p. 198.
- [7] AHPA – AWWA, Standard Method for Water and Wastewater Examination, 17th Edition, American Public Health Association/America Water Works Association, Washington, DC, 1992.
- [8] Ramalho, R.S., (1983). *Introduction to Wastewater Treatment Processes*, Academic Press Inc, second edition



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