Biological Wastewater Treatment in Reactors with Fibrous Packing

By H. H. P. Fang,[1] and C. L. Y. Yeong[2]

Abstract: Three sets of experiments were conducted to study the effects of hydraulic retention time (HRT), elevated ammonium nitrogen (NH_3-N) concentration and system breakdown on the removal of chemical oxygen demand (COD) and nitrogen in wastewater. Each set of experiments was conducted in parallel using three 21.7-L reactors with submerged fibrous packing. One reactor was aerated continuously, and the other two were aerated half the time intermittently. When tested with synthetic wastewater having an average COD of 958 mg/L and NH_3-N of 94 mg/L at 4–14 hr of HRT, all reactors had similar levels of carbonaceous oxidation (95–97%) and nitrification (85%). The nitrite/nitrate produced were effectively denitrified in the intermittently aerated reactors because of the anoxic condition in the interior of the "bio-pompons"; but the continuously aerated reactor had little denitrification activity. Elevated NH_3-N concentrations were toxic to microorganisms in all reactors, affecting adversely both the nitrification and carbonaceous oxidation. Nitrification was affected more in the intermittently aerated reactors; and carbonaceous oxidation was affected more in the continuously aerated reactor. All reactors showed rapid recovery from a simulated system breakdown.

INTRODUCTION

Biological wastewater-treatment processes can be classified as either attached growth or suspended growth. In the attached-growth process, microorganisms are immobilized on a support surface, forming biofilms. Substrates in the wastewater are absorbed into the film and gradually degraded by the microorganisms. In the suspended-growth process, the microorganisms in suspension have more-intimate contact with the substrates. The attached-growth process seems to be more stable than the suspended-growth process when the wastewater has considerable fluctuations in flow rate and concentrations (*Nutrient* 1983; Toda and Ohtake 1985). Limitation of mass transfer can effectively shield the microorganisms from the shock loadings of substrates and toxins. Furthermore, even if the growth rate of the biomass is reduced by this adverse condition, the population of microorganisms can still be maintained since they are physically retained in the system (Stevens 1988). This is unlike the situation in suspended-growth reactors, where the population of microorganisms can decrease through the sludge loss from effluent and wastage if the growth rate cannot compensate the loss.

In addition, the attached-growth process could also be more effective for nitrification. Nitrifiers tend to have slow growth rates. For the activated-sludge process, the sludge-retention time (SRT) is normally kept at 10 days or longer in order to carry out nitrification effectively. In the attached-growth process, however, the biomass includes nitrifiers that tend to grow well on the support surface and characteristically have long SRT since they

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are retained in the biofilm. Moreover, the interior of the biofilm has a low concentration of dissolved oxygen (DO), which could likely create an anoxic condition for denitrification.

An ideal packing material for the attached-growth process should not only be inexpensive, light, durable, easy to ship and install, it should also have a large specific surface area for bacteria growth and high porosity to prevent clogging by the increased biomass. Materials used in the past include stone, coke, ceramic materials, pall rings, plastic honeycomb, and corrugated sheets. Novel packing materials include ring lace (Iwai et al. 1990; Lessel 1991), net plates (Nambu et al. 1991), and fibrous materials (Fang et al. 1991; Huang and Hung 1986).

In this study, synthetic wastewater was treated in three laboratory-scale reactors filled with fibrous packing materials. Two reactors were aerated intermittently and the other was aerated continuously. The performances of these reactors are compared under various experimental conditions.

EXPERIMENTAL

Three sets of experiments were conducted to study the effects of hydraulic retention time (HRT), elevated ammonium nitrogen (NH_3-N) and system breakdown on the removal of chemical oxygen demand (COD) and nitrogen in wastewater. Each set of experiments was conducted in parallel using three plexiglass reactors, each with an internal diameter of 124 mm, height of 2 m, and an effective volume of 21.7 L. Fig. 1 illustrates the setup. A string of rayon fiber bundles was affixed at the centerline of each reactor. The bundles were evenly spaced at 60-mm intervals. Fig. 2 illustrates the two

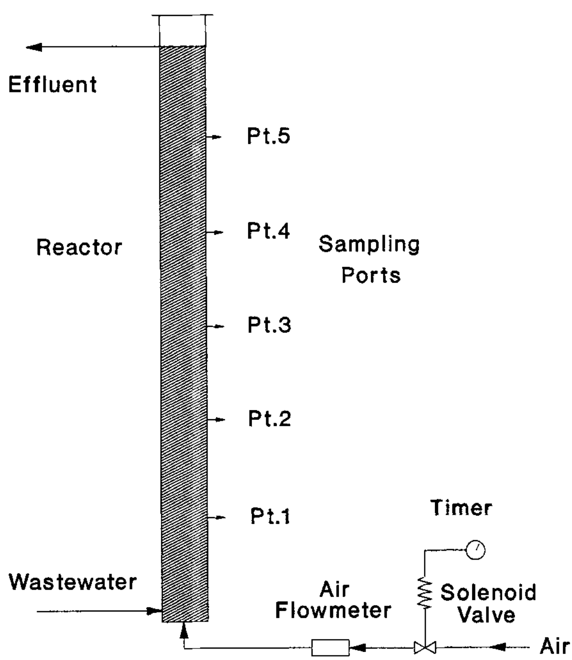

FIG. 1. Reactor Setup

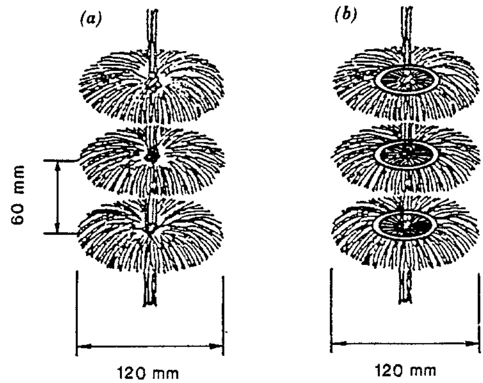

FIG. 2. Fibrous Packing Materials: (*a*) Type 1; (*b*) Type 2

similar types of fibrous materials used in this study. The fibers in the type 1 bundles were tied by a knot in the middle, like a pompon, allowing the fibers to suspend in water at radial directions. The fibers in the type 2 bundles were held by two flat plastic rings 25 mm from the center, allowing the fibers to suspend only at the periphery. These packings are lightweight and have a high specific surface area and porosity. Further, the fibers in suspension can avoid the possibility of clogging, a phenomenon that frequently arises in other types of packing media. In the experiments, Reactors 1 and 2 were filled with type 1 packing, whereas reactor 3 was filled with type 2.

All reactors were seeded with settled sludge from the Shatin wastewater-treatment plant, in Hong Kong, and were aerated by diffused air. Reactor 1 (designated CA) was aerated continuously. Reactors 2 (designated IA1) and 3 (designated IA2) were aerated intermittently by turning the diffused air on and off every 2 hr using a timer and solenoid valves. During the air-on period, mixing was created by the diffused air. There was, however, neither mechanical mixing nor recirculation during the air-off period.

To prevent premature degradation, wastewater was kept at 4°C in a feed tank. It flowed through a heater to be warmed to 21°C before being fed into individual reactors. Throughout the experiments, wastewater was fed into the reactors continuously and the temperature in the reactors was kept at a constant of 21°C.

The first set of experiments was conducted using a synthetic wastewater with an average COD of 958 mg/L, NH_3-N of 94 mg/L, and phosphorus of 40 mg/L. The HRT varied from 4 to 14 hr, corresponding to a COD loading rate of 1.6–5.6 kg/m^3·d. The constituents in 100 L of the synthetic wastewater included about 14 g of dry milk powder, 78 g of sucrose, 38 g of ammonium chloride, 7 g of potassium di-hydrogen phosphate, 14 g of potassium hydrogen phosphate, and 75 g of sodium bicarbonate.

The synthetic wastewater, which had an average total suspended solids (TSS) of 32 mg/L, was composed of 97% soluble COD, and only 3% insoluble COD. The TSS in the effluent ranged from 237 to 662 mg/L, of which 98% was volatile suspended solids (VSS). In full-scale operations, solids in the effluent would have to be further removed probably by settling. Since attached-growth reactors do not require recycling of settled sludge, the postaeration settling was not included in this study. Under steady-state conditions, the sludge yield could be calculated from the effluent VSS and the COD removed, assuming the VSS was primarily biomass. The degrees of COD removal in this study were calculated by comparing the soluble COD in the effluent and the total COD in the synthetic wastewater.

A second set of experiments was conducted to test the toxic effect of ammonium on the removal of COD and nitrogen. The COD was kept at an average of 840 mg/L, while the NH_3-N concentration was increased stepwise from 83 to 225 mg/L. The dosage of sodium bicarbonate was increased in proportion to NH_3-N to provide sufficient inorganic carbon and alkalinity. The HRT was kept at 12 hr.

A final experiment was conducted to test the response of each reactor to system breakdown. The reactors were reacclimated with wastewater of a similar strength to that used in the first set of experiments for 17 days until steady-state conditions were reached. The wastewater feed and aeration were then abruptly shut down to simulate a breakdown. After seven days, wastewater feeding and aeration were resumed, and the effects of the shutdown on the removal of COD and nitrogen were examined.

During each experiment, effluent quality was initially monitored every three days for COD, NH_3-N, nitrite/nitrate nitrogen (Ox-N), VSS, and TSS. The effluent quality was then monitored daily after one week or 20 times the HRT, whichever was longer, had passed. A steady-state condition was assumed to have been attained when variations in the effluent COD and NH_3-N were less than 20 and 5 mg/L, respectively, over three consecutive days. For reactors IA1 and IA2, 2-hr composite samples were taken for both air-on and air-off periods. The analytical procedures, including COD, NH_3-N, VSS, TSS, alkalinity, etc., were as outlined in the *Standard Methods for the Examination of Water and Wastewater* (1985). Dissolved oxygen was measured using a YSL Model 57 dissolved-oxygen meter and pH was measured using an Orion SA720 pH/ISE meter with a glass electrode. A Technicon Autoanalyzer II was used for Ox-N analysis using the automated cadmium reduction method. Organic nitrogen, which contributed to only 3% of the total nitrogen (TN) in the wastewater, was not monitored.

RESULTS

COD and Nitrogen Removal

Reactors under aeration were operated at a near complete-mix mode, which was evidenced by the constant COD concentration in solution samples taken at various height levels of the reactors. However, during the air-off period, the two intermittently aerated reactors were operated at a near plug-flow mode, as illustrated in Fig. 3. During the air-off period, the wastewater continued to flow into the bottom of the reactor, causing the solution at the top of the reactor to overflow. Because of the lack of air mixing and the slowdown of biodegradation, the COD concentration near the bottom of the reactor was close to that of the wastewater. But, the effluent COD remained at the low levels as at the end of the preceding air-on period.

When the aeration restarted, the bulk solution was completely mixed and the COD level in the effluent would increase briefly. However, because the aerobes in the reactors had been starved for 2 hr, not only could they biodegrade the substrates at high rates but they also had the capacity to sequester substrates in the bulk solution. A study of sequencing batch reactors using similar packings (Fang et al. 1991) showed that about 50% of the substrate in the bulk solution could be sequestered in only about 4 min. Although the effluent quality during the initial air-on period was poor, it had little effect on the overall quality of the time-composite effluent.

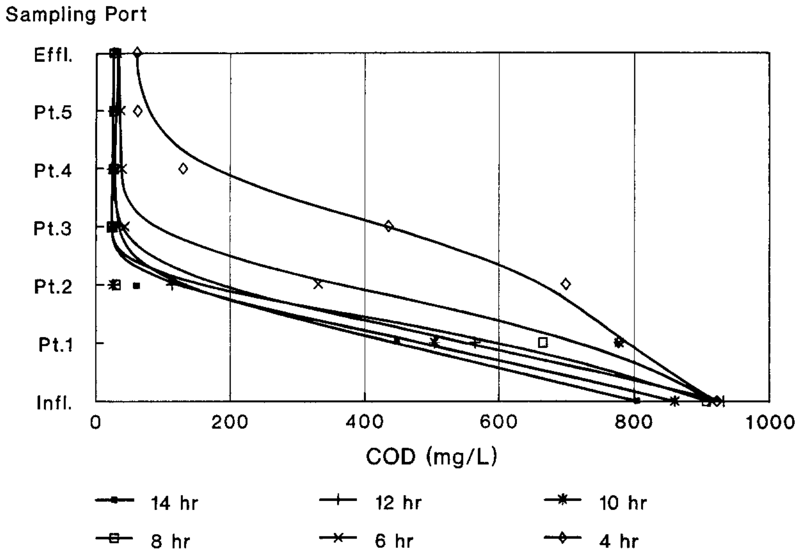

FIG. 3. Typical COD Profiles during Air-Off Period in Intermittently Aerated Reactors

TABLE 1. COD in Wastewater and Effluents at Various HRT

HRT (hr) (1)	Synthetic wastewater (mg/L) (2)	Reactor CA (mg/L) (3)	Reactor IA1		Reactor IA2	
			Air on (mg/L) (4)	Air off (mg/L) (5)	Air on (mg/L) (6)	Air off (mg/L) (7)
4	941	41.5	56.4	60.4	34.6	47.0
6	933	49.0	33.7	31.1	28.8	23.6
8	987	46.5	28.2	27.1	25.9	22.1
10	963	63.5	27.9	26.3	26.3	24.0
12	1,014	52.6	29.7	26.6	32.0	30.5
14	909	30.1	34.0	33.2	34.0	34.7

During aeration, thé DO in the bulk solution was kept at 5 mg/L or higher. When air flow was turned off, the DO in the effluent decreased gradually to less than 0.1 mg/L in about 30 min. When air flow was turned on in the subsequent air-on period, it took 10–30 min for the DO in the bulk solution to reach the constant level. The DO inside the bio-pompons could not be directly measured.

Results for the first set of experiments are summarized in Tables 1–3, which show the COD, NH_3-N, and Ox-N concentrations, respectively, in both wastewater and effluents for various HRT ranging from 4 to 14 hr. Throughout this study, it was found that there was little difference between the effluent samples collected during air-on and air-off periods. Consequently, the effluent quality is represented by the average of the two periods. In addition, the qualities of effluents from reactors IA1 and IA2 were comparable, despite the slight difference in their packings.

Fig. 4 illustrates that all reactors removed COD effectively over a wide

TABLE 2. NH_3-N in Wastewater and Effluents at Various HRT

HRT (hr) (1)	Synthetic wastewater (mg/L) (2)	Reactor CA (mg/L) (3)	Reactor IA1 Air on (mg/L) (4)	Reactor IA1 Air off (mg/L) (5)	Reactor IA2 Air on (mg/L) (6)	Reactor IA2 Air off (mg/L) (7)
4	98	58.3	65.0	60.4	65.6	62.1
6	97	59.1	60.7	56.4	61.6	60.9
8	99	56.3	53.2	49.0	48.8	44.7
10	96	57.1	41.5	38.3	38.5	35.9
12	85	18.4	19.1	17.1	10.8	8.6
14	88	8.3	13.0	10.6	6.0	5.1

TABLE 3. Ox-N in Wastewater and Effluents at Various HRT

HRT (hr) (1)	Synthetic wastewater (mg/L) (2)	Reactor CA (mg/L) (3)	Reactor IA1 Air on (mg/L) (4)	Reactor IA1 Air off (mg/L) (5)	Reactor IA2 Air on (mg/L) (6)	Reactor IA2 Air off (mg/L) (7)
4	0.0	0.1	0.0	0.0	0.0	0.0
6	0.0	0.4	0.0	0.0	0.0	0.0
8	0.0	5.2	0.5	0.0	1.2	0.2
10	0.0	9.0	1.6	0.4	2.5	0.9
12	0.0	42.0	5.2	2.1	6.2	4.1
14	0.0	51.6	4.7	3.3	4.8	5.4

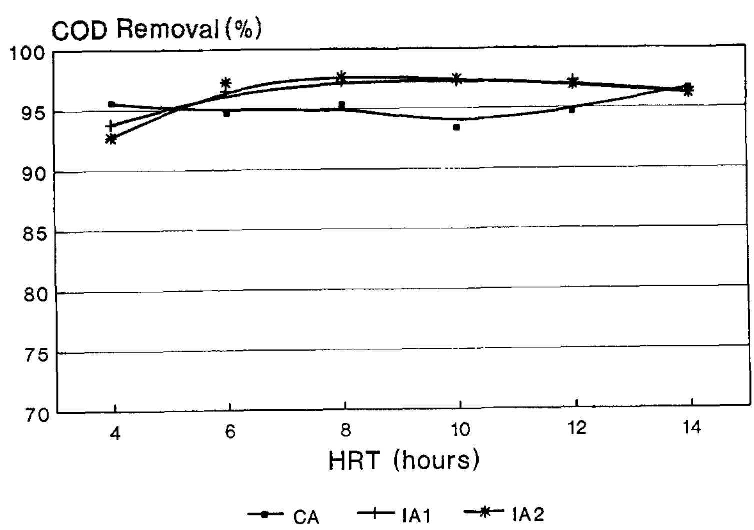

FIG. 4. COD Removal Efficiency at Various HRT

range of HRT of 4–14 hr. Reactor CA performed consistently, removing on average 95% of COD from the wastewater. Reactors IA1 and IA2, although only aerated half of the time, removed on average 96% of COD. But they only removed 95% of COD when operated at 4 hr of HRT, because of insufficient aeration. For HRT of 6–14 hr, they on average removed 97% of COD, which is slightly superior to the 95% average removal by reactor CA.

Sludge yields could be estimated, based on the VSS and COD data in the wastewater and the effluent. For each gram of COD removed, Reactors IA1 and IA2 produced on average 0.39 g of VSS; and reactor CA produced 0.49 g. Both were within the range of 0.39–0.52 g VSS/g COD, as reported by Huang et al. (1983).

A precise balance of nitrogen requires accurate measurements of nitrogen content in the VSS of effluent. NH_3-N available for nitrification is then equal to the NH_3-N in the influent minus the nitrogen content in the effluent VSS. Total amount of NH_3-N being nitrified is equal to the NH_3-N available minus soluble NH_3-N in the effluent. The degree of nitrification of NH_3-N available is represented by percentage of NH_3-N available being nitrified. Furthermore, the amount of nitrogen gas (N_2) produced by denitrification can be calculated by the amount of NH_3-N nitrified minus soluble Ox-N in the effluent.

The nitrogen content in the VSS of effluent was unfortunately not measured in this study. The degrees of nitrification and denitrification could, however, be estimated using a reasonable assumed value. The following discussion is based on the assumption that the effluent VSS contained 8.5% nitrogen, since Christensen and Harremoes (1977) reported that the biomass of activated sludge contains 7–10% of nitrogen. Using another assumed value slightly deviated from 8.5%, say 7% or 10%, would not qualitatively affect the following discussion.

Fig. 5 illustrates that degrees of nitrification are comparable in all three reactors, even though reactors IA1 and IA2 were only aerated half of the

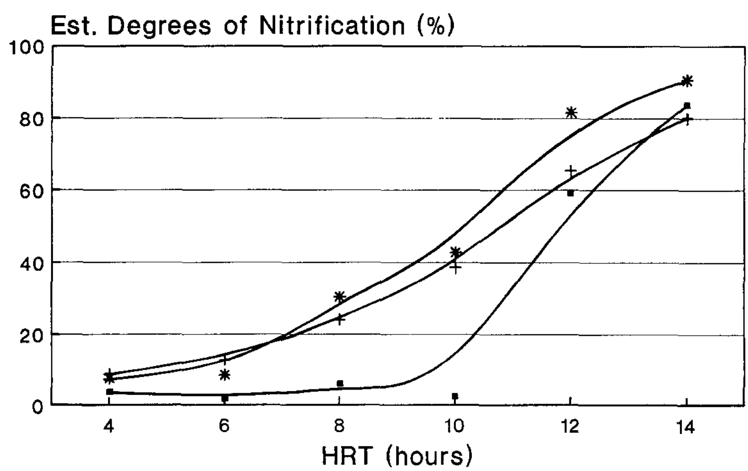

FIG. 5. Estimated Degrees of Nitrification of NH_3-N Available at Various HRT

time. Fig. 5 also illustrates that nitrification of NH_3-N available in all reactors increased with HRT, from about 10% at 4 hr of HRT to about 85% at 14 hr. Comparison of Figs. 4 and 5 shows a much higher rate for carbonaceous oxidation than nitrification, as expected. It took less than 4 hr of HRT to remove about 95% of COD, but it required 14 hr to nitrify 85% of NH_3-N.

Table 3 shows that the Ox-N in all reactors increased with HRT. The Ox-N level in the effluent was as high as 52 mg/L in reactor CA, and 5 mg/L or less in reactors IA1 and IA2. This clearly indicates the lack of denitrification in reactor CA. Fig. 6 illustrates that the estimated amounts of N_2 produced by denitrification, which increased with HRT in reactors IA1 and IA2, from about 5 mg/L at 4 hr of HRT to about 45 mg/L at 14 hr. On the other hand, the amounts of N_2 produced in reactor CA were insignificant for all HRTs.

In reactor CA, the DO in the bulk solution was kept at a minimum of 5 mg/L, causing DO to diffuse into the interior of the bio-pompon to the level that would suppress denitrification. On the other hand, the DO in the bulk solution of reactors IA1 and IA2 was cyclically depleted during the air-off period. Thus, the DO in the interior of the bio-pompon was conceivably depleted most of the time, as evidenced by its dark appearance. The Ox-N generated by nitrification in the bulk solution diffused into the bio-pompon, resulting in denitrification, as illustrated in Fig. 6.

Iida and Teranishi (1984) used "rectiform plastic media" and intermittent aeration to treat municipal wastewater in their pilot study. However they found that for medium-strength wastewater (BOD 200 mg/L and NH_3-N 40 mg/L) recycling of effluent is required for achieving 70% or higher removal of total nitrogen. Results indicate that reactors having the fibrous packing studied could accomplish over 80% of total nitrogen removal even at a higher level of influent NH_3-N (94 mg/L) and without effluent recycling.

The pH in all reactors was kept within 7.2–7.6 throughout this set of experiments except in the experiment with 14 hr of HRT, in which the

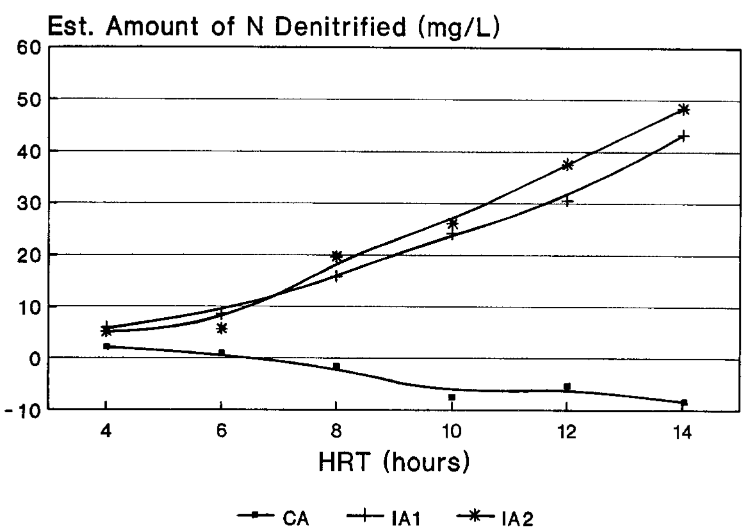

FIG. 6. Estimated Amounts of N_2 Produced by Denitrification at Various HRT

alkalinities in reactors IA1, IA2, and, especially, CA were low (190, 159, and 20 mg/L, respectively) due to nitrification. The corresponding pH levels in the reactors were 7.4, 7.3, and 4.7. The alkalinity and, consequently, the pH in reactor CA were lower than the levels measured in the other two reactors because so little denitrification took place in reactor CA. However, the effluent from reactor CA was composed of 51.6 mg/L of Ox-N, and 8.3 mg/L of NH_3-N, which seems to indicate that the low pH did not seriously affect the nitrification.

Ammonium Toxicity

In the second set of experiments, the HRT was kept at 12 hr. The average COD in wastewater was 840 mg/L, while the NH_3-N in wastewater was increased stepwise from 83 to 225 mg/L. The pH level in reactors CA, IA1, and IA2 was kept between 7.3 and 8.4, indicating the pH level in reactor CA had recovered from the low pH at the last run of the previous experiments. The DO was kept at 5 mg/L or higher in reactor CA all the time and in reactors IA1 and IA2 during the air-on period. Fig. 7 illustrates that as the NH_3-N concentration increased, the percentage of COD removal in all reactors decreased, indicating the toxic effect of ammonium. When NH_3-N was increased from 83 to 225 mg/L, the COD removal in reactor CA was reduced from 94% to 85%. The COD removals in reactors IA1 and IA2 were reduced to a lesser degree, from 97% to 94%. This seems to indicate that the ammonium was more toxic to the aerobic microorganisms in reactor CA. On the other hand, the microorganisms carrying out carbonaceous oxidation in reactors IA1 and IA2, which were composed of not only aerobic but also facultative and anaerobic microorganisms, were less sensitive to the ammonium, as reported by McCarty and McKinney (1961) and Hobson and Shaw (1976). Fig. 8 illustrates that ammonium also inhibited nitrification in all reactors, as reported by Anthonisen et al. (1976), and Mines and Sherrard (1985). However, the inhibitory effect seemed to be more severe in reactors IA1 and IA2 than in reactor CA. When tested against the waste-

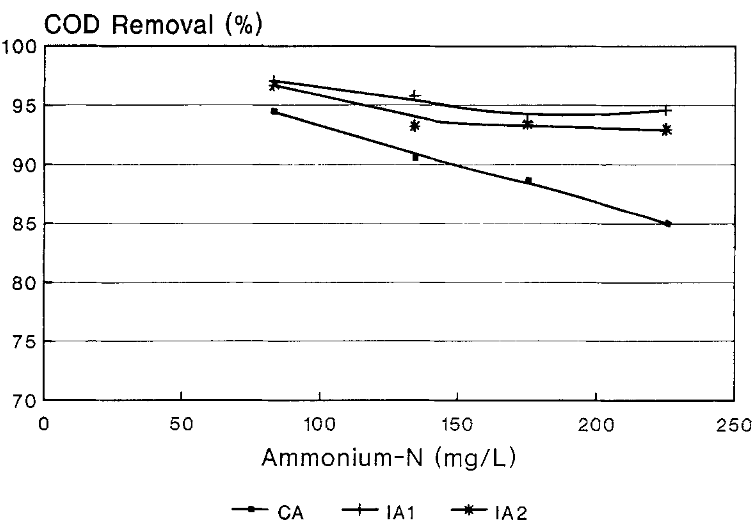

FIG. 7. COD Removal Efficiency at Various NH_3-N Concentrations

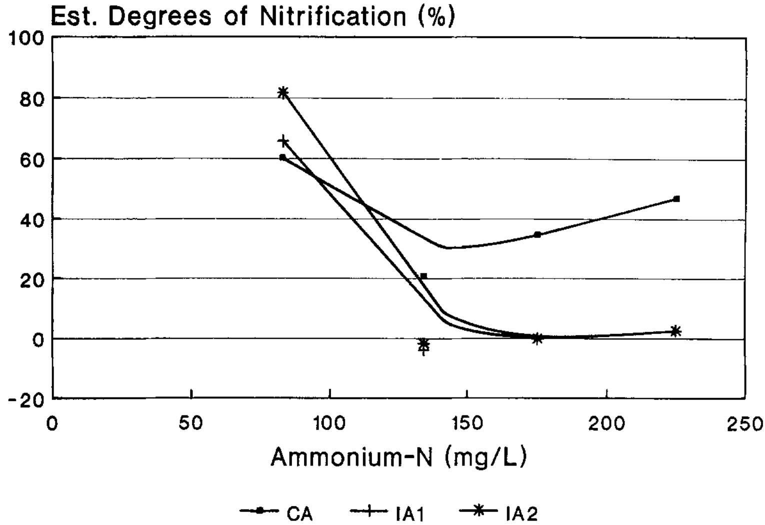

FIG. 8. Estimated Degrees of Nitrification of NH_3-N Available at Various NH_3-N Concentrations

water with 83 mg/L of NH_3-N, about 60% and 70%, respectively, of NH_3-N available was nitrified in reactor CA and in reactors IA1 and IA2. When the NH_3-N in wastewater increased to 225 mg/L, about 40% of NH_3-N available was nitrified in reactor CA, but little nitrification was detected in reactors IA1 and IA2. The effluent from reactor CA contained 105 mg/L of NH_3-N and 71 mg/L of Ox-N; the effluent from reactors IA1 and IA2 contained 197 mg/L of NH_3-N and less than 2 mg/L of Ox-N.

Simulated System Breakdown

After the second set of experiments, reactors were reacclimated with wastewater of about 1,000 mg/L of COD and 100 mg/L of NH_3-N. When steady-state conditions were reached, after 17 days, wastewater feed and aeration were stopped abruptly to simulate a system breakdown. Normal feeding and aeration resumed seven days after the breakdown. Before the breakdown, the bulk solutions had an average COD of 50 mg/L. After seven days of breakdown, the bulk solution COD became 341 mg/L in reactor CA and averaged 834 mg/L in reactors IA1 and IA2. The increase in COD resulted from the anaerobic biodegradation of the biomass retained in the reactors. The higher COD concentrations in reactors IA1 and IA2 were likely due to the higher degrees of anaerobic activities by the facultative and anaerobic microorganisms in the two reactors.

When normal wastewater feeding and aeration resumed seven days after the breakdown, all reactors readily recovered their ability to remove COD. After one day, the COD in all effluents was reduced to the 30–45 mg/L range, and was kept at that level until the experiment stopped, 28 days later. During this period, reactors IA1 and IA2 removed about 97% of COD, which was, again, slightly superior to reactor CA, which removed 95% of COD. Nitrification activity in reactor CA also recovered rapidly to the same level as in the first set of experiments. Nitrification activity in reactors IA1 and IA2 was not as consistent as in the first set of experiments.

CONCLUSIONS

The following conclusions are drawn from the results of the parallel experiments conducted using three 21.7-L reactors with submerged fibrous packings.

Reactors incorporated with the novel fibrous packing materials effectively removed 95–97% of COD and nitrified up to 85% of NH_3-N available when tested with synthetic wastewaters having an average COD of 958 mg/L, NH_3-N of 94 mg/L with 4–14 hr of HRT, regardless of whether they were aerated intermittently or continuously.

The cyclic DO depletion in the intermittently aerated reactors created an anoxic environment in the interior of the bio-pompons for denitrification. The amounts of N_2 produced increased with HRT. About 45 mg/L of NH_3-N was eventually converted to N_2 at 14 hr of HRT. Little denitrification activity took place in the continuously aerated reactor at all HRT.

Elevated NH_3-N concentrations in wastewater had adverse effects for all reactors. The continuously aerated reactor was affected more on carbonaceous oxidation; and the two intermittently aerated reactors were affected more on nitrification.

All reactors readily recovered their abilities to remove COD after seven days of system breakdown.

Results from this study show promising advantages of using fibrous packing materials in the reactors and the technique of intermittent aeration for the effective removal of COD and nitrogen from wastewater.

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