

A Comparison of Floating and Sunken Media Biological Aerated Filters for Nitrification

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Abstract: The versatility of the biological aerated filter (BAF) has made it an important process in wastewater treatment. These submerged three-phase fixed media reactors have been used in a wide variety of applications in wastewater treatment, such as primary treatment (solids removal), secondary treatment (COD and BOD removal), and tertiary treatment (nitrification). The aim of this work was to investigate the biological start-up of two such reactors to remove suspended solids (SS), total COD (tCOD) and ammonia, one containing a sunken medium (relative density 1.05) and the other containing a floating medium (relative density 0.92), both identical in shape and size. The reactors (0.054 m³ media) were run in parallel in upflow mode using secondary effluent as the process liquid at a flowrate of 0.2 dm³ min⁻¹ and air : liquid ratio of 10 : 1. Overall, floating media performed better than sunken media for SS, tCOD and ammonia removal, probably due to the compression of the bed due to the buoyancy force of the media and the flow of air and liquid acting upwards. Bed compression improved solids removal and appeared to have promoted the growth of bacteria. Temperature had a greater impact on nitrification than on carbonaceous matter removal. The floating medium reactor was more resistant to low temperature shocks than the sunken medium reactor but the latter showed a faster recovery time as temperature increased. Although the backwashing frequency used was satisfactory, performance may have improved if the backwashing had been carried out only when reactor performance began to decline. Nitrification was shown to follow a reaction rate between zero and half order. Thus, ammonia removal was generally independent of ammonia concentration and more affected by the presence of carbonaceous matter. © 1998 SCI

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Key words: biological aerated filter (BAF); nitrification; plastic media; backwashing; temperature

INTRODUCTION

The biological aerated filter (BAF) has been developed over the last 20 years and has become an alternative to other wastewater treatment systems, i.e. trickling filters

and activated sludge, due to its small footprint size and high loading capability. The BAF is a fixed film biological process and can be used for the simultaneous removal of carbonaceous matter, ammonia and solids.¹

Many factors affect the start-up and performance of fixed-film nitrifying reactors. Biological factors such as the establishment of predators (rotifers) as well as physical factors such as the reactor's hydrodynamics and the hydraulic residence time affect both biofilm growth and nutrient removal.² The hydrodynamics of reactors vary with the media used, liquid flowrate and aeration rates.³ Turbulent conditions will affect both the type of biofilm growth and surface attachment.⁴ Increased turbulence causes reduced biomass concentrations within reactors

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through shear but improves substrate flux when substrate concentrations are non-limiting.⁵ The filtration capacity of the reactor will change its hydrodynamic configuration, which can cause variable conditions within reactors that may inhibit nitrification efficiency.⁶

The operating residence time within reactors will primarily depend on two factors, the temperature of the process liquid and the concentration of the nutrients in the influent to be treated.⁷ The performance of many biological systems is dependent on temperature.⁸ However, variable temperatures have been found to have little effect on the performance of BAF reactors except at extreme temperatures.^{9–11} Performance at low temperatures has been improved by simply increasing the retention time.^{7,8,12}

Substrate concentrations of the influent wastewater affect the nitrification rate and the biomass growth within BAF reactors.¹³ Chemical substances such as fluoride inhibit the nitrification process non-competitively.¹⁴ Nitrifying (autotrophic) bacteria require some carbonaceous matter for their assimilation but high concentrations of carbonaceous matter will promote the growth of carbonaceous-removing (heterotrophic) bacteria, resulting in competitive inhibition.¹⁵ High BOD also utilises a large part of the oxygen available to the nitrifiers which require high oxygen concentrations to metabolise.^{7,16} Moreover, the concentration of suspended solids should be kept low as these will promote heterotrophic biofilm growth, hence inhibiting nitrification.^{16,17} Ammonia concentration in the feed is important primarily when start-up is taking place. High ammonia concentrations increase nitrifying biofilm development, leading to a short start-up time.^{7,12} Ammonia removal through oxidation is required in preference to assimilation as only oxidised nitrogen may be removed through denitrification.¹⁸ Assimilated nitrogen may only be removed through biofilm removal by backwashing. Thus long biomass residence times of around 5 days are required (compared with 12–24 h for secondary processes) to allow the majority of the ammonia to be oxidised.¹⁹

BAFs are designed with a range of variations of flow directions or types of media used.¹ Despite the fact that there are currently a great number of papers on BAFs, very few make a direct comparison between upflow/downflow conditions and/or floating/sunken media performance. The objectives of this work were to investigate the start-up performance of parallel sunken and floating media reactors for SS, tCOD and ammonia removal and the effect of low temperatures on treatment efficiency.

2 MATERIALS AND METHODS

Experiments were carried out using two identical polyvinylchloride (PVC) reactors run in parallel. Each

reactor was cylindrical in shape with an overall height of 2 m and diameter of 0.2 m. The media height within the reactors was 1.7 m with a total volume of 0.054 m³. Liquid influent was introduced at the base of each column using a 5 cm filter nozzle (Degremont, Dunstable, UK) and aeration was carried out using three identical nozzles placed around the base plates. Sample ports were placed at 20 cm intervals along the length of the reactor and a port was placed on the base of each reactor to allow removal of sludge and liquid from the bottom of the reactors. The media were kept in place using rigid polypropylene mesh with 1.5 mm holes which was held in place at the top of the reactors using clamps.

The media used were made of recycled polypropylene (Cookson plc, Cheshire, UK) which was re-extruded to form a medium with a relative density 0.92 (floating) and mixed with a calcium carbonate filler (40%) to form a medium identical in shape and size but with a relative density of 1.05 (sunken). Each medium was cylindrical with a diameter of 2.4–2.7 mm and length 4–6 mm. The media had a surface area of 1160 m² m⁻³ and a voidage of 42%.

The process liquid used in the study was partially nitrified secondary sewage from Cranfield University's sewage treatment works. The sewage was passed upflow through the reactors at a flowrate of 0.2 dm³ min⁻¹ with a residence time of 2 h. Aeration was carried out at a rate of 2 dm³ min⁻¹ (air : liquid ratio of 10 : 1). Backwashing was carried out on a weekly basis after an initial start-up period to remove excess biomass. During backwashing the influent air and liquid flows were shut-down and 2.5 dm³ of liquid were drained from the bottom of the reactors. Following this, air scour was carried out at a rate of 25 dm³ min⁻¹ for 1 min. The reactors were left for 2 min and a further 7.5 dm³ of liquid were drained. The process air and liquid were then resumed. Analysis of suspended solids (SS), soluble chemical oxygen demand (sCOD), total COD (tCOD), ammonia, nitrates and nitrites were made every alternate day according to standard methods.²⁰ Temperature, dissolved oxygen (DO) and pH were checked daily. Influent temperature was controlled by means of a temperature controller. Off-gas measurements of oxygen in the inlet and outlet were carried out occasionally with an ADC7000 Oxygen Off Gas Analyser (ADC, Hertfordshire, UK).

3 RESULTS AND DISCUSSION

In BAFs, influent nutrient quality, temperature, backwashing rate and oxygen availability have been found to be rate limiting steps for nitrification. High levels of oxygen are required for nitrification to take place.^{16,21} At the aeration rate used in this study, DO concentrations in the effluent remained high at 5 mg dm⁻³ or greater. Off-gas measurements of the air leaving the

reactors showed no apparent reduction in oxygen concentrations (resolution > 0.1%), subsequently it was assumed that oxygen limitation did not inhibit the performance of the reactors. Throughout the experimental period the pH remained between 7.6 and 8.2 which was in the optimum range for nitrification.⁷ Table 1 presents the performance of sunken and floating media during start-up and steady-state.

Over the first 15 days of start-up, influent nutrient levels remained low at 25–75 mg dm⁻³ SS (Fig. 1(a)), 50–140 mg dm⁻³ tCOD (Fig. 1(b)) and 1–5 mg dm⁻³ NH₃-N (Fig. 1(c)). Over this period the SS removal reached a maximum value of 57% for the sunken medium and 78% for the floating medium (Fig. 2(a)). Similarly, tCOD removal reached a maximum performance of 71% in the floating medium compared with 58% in the sunken medium (Fig. 2(b)). Ammonia removal was also highest in the floating medium, attaining a maximum of 60% with only 40% in the sunken medium (Fig. 2(c)).

On day 15 a temperature shock was carried out during which the mean reactor temperature was reduced from 8 to 4°C with a corresponding increase in SS, tCOD and ammonia loading. After a period of 3 days during which the reactor temperature was maintained at 3–5°C, the temperature was returned to 8 ± 3°C and then kept at a high nutrient loading.

Increased nutrient loading and reduced temperature showed the greatest effect on the sunken medium performance. SS, tCOD and ammonia removal dropped rapidly to almost 0% (Fig. 2) while in the floating medium almost no effect was seen in SS and tCOD removal and ammonia removal rate showed some reduction. After 7 days at the higher nutrient loadings and following the temperature shock, the performance

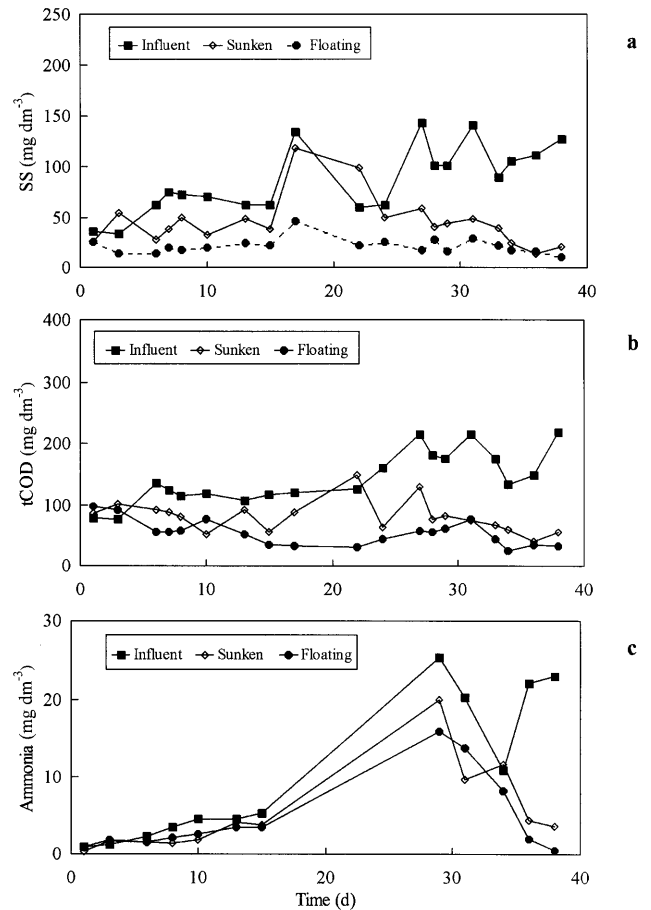


Fig. 1. Suspended solids (a), total COD (b) and ammonia (c) concentration in influent and effluent during start-up.

of the sunken medium in SS removal dropped to 0% with only a reduction of 4% in the floating medium (Fig. 2(a)). There was then a rapid increase in performance with a maximum of 89% removal in the

TABLE 1
Mean Values and Ranges (in parentheses) of Influent and Effluent Parameter Concentration during Start-up and Shock Loading

	Influent		Effluent sunken medium		Effluent floating medium	
	Start-up	Shock load	Start-up	Shock load	Start-up	Shock load
Suspended solids (mg dm ⁻³)	59 (34–74)	103 (60–143)	39 (26–54)	52 (155–118)	20 (14–26)	23 (11–46)
Soluble COD (mg dm ⁻³)	46 (38–63)	51 (40–64)	35 (30–43)	38 (22–58)	38 (29–50)	27 (15–77)
Total COD (mg dm ⁻³)	107 (77–135)	170 (127–220)	80 (52–101)	79 (41–148)	67 (36–98)	46 (25–77)
Ammonia (mg dm ⁻³)	3.2 (0.9–5.4)	20.3 (9.9–24.2)	2.1 (0.4–4.2)	9.9 (3.7–20)	2.3 (1.0–3.6)	8 (0.5–15.8)
Nitrites (mg dm ⁻³)	0.41 (0.24–0.6)	0.52 (0.22–0.7)	0.34 (0.27–0.4)	0.44 (0.22–0.6)	0.64 (0.32–0.9)	0.23 (0.02–0.4)
Nitrates (mg dm ⁻³)	3.7 (2.5–4.4)	3.4 (1.2–6.2)	4.4 (2.2–5.9)	4.9 (3.8–7.0)	4.2 (3.3–6.0)	4.6 (2.9–6.0)

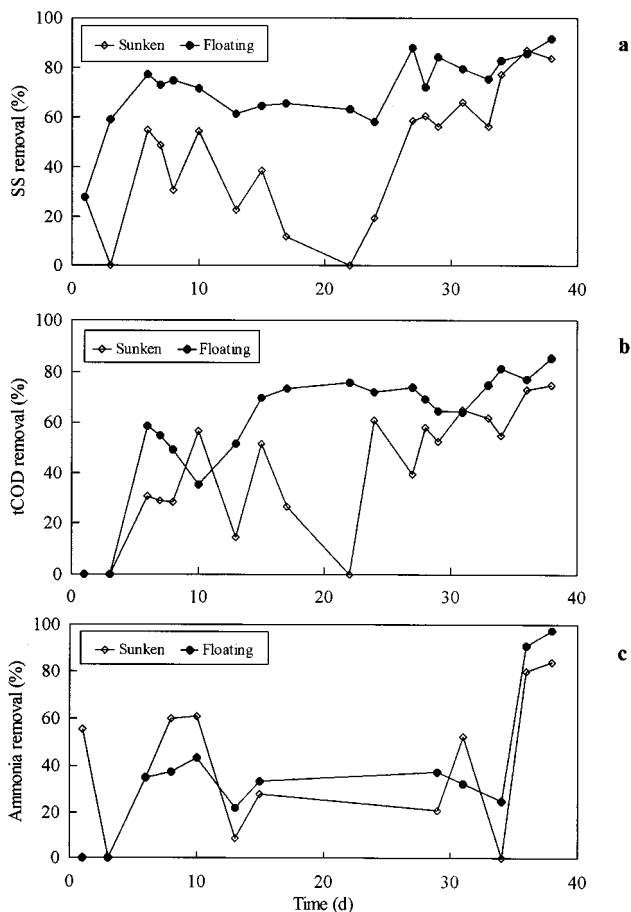


Fig. 2. Suspended solids (a), total COD (b) and ammonia (c) removal in sunken and floating media during start-up.

sunken medium and 83% in the floating medium. The floating medium performance was better than that for the sunken medium in tCOD removal, with virtually no effect on the removal rate in the floating medium but a rapid drop in the performance of the sunken medium over the first 7 days following temperature shock (Fig. 2(b)). After 25 days at the higher loading (day 40), removal rates reached 88% in the floating medium from a value of 71% 7 days after the temperature shock. This compares with a value of 79% in the sunken medium which rose from a value of 0% following the temperature shock. These results showed that the floating medium was able to withstand shock loadings in terms of SS and tCOD removal. On the other hand, the sunken medium tended to show initial poor response and required several days to recover although the following recovery was rapid. On the other hand, nitrification studies revealed an improvement in ammonia removal performance in both media types with the higher ammonia loading though recovery took longer (Fig. 2(c)). The removal profiles were similar in shape compared with those for SS and tCOD removal and again the floating medium performed better than the sunken medium.

After day 40, SS, tCOD and ammonia removal rates decreased and some clogging of the reactors was

observed. It was thus decided to backwash on day 44. Over the 5 days following backwashing, SS and tCOD removal in the sunken medium remained very low (Fig. 3(a and b)). Following a rapid increase in performance over the next 2 days there was a subsequent decrease in SS and tCOD removal until backwashing was repeated 21 days after the first backwashing. Although the performance of the floating medium was also affected by backwashing, the effect was not as great. Unlike the sunken medium which showed an initial decrease in ammonia removal, the floating medium showed an immediate increase in nitrification following backwashing (Fig. 3(c)). Ammonia removal reached a maximum value of 98% in the floating medium and 91% in the sunken medium. A performance similar to that of SS and tCOD removal was seen with a rapid drop in removal rates following an initial peak (Fig. 3(a and b)). Backwashing was repeated only every 21 days (days 65 and 86). The performance of the reactors remained variable and unstable over the 56 days following the first backwash.

SS removal rates of approximately 50% have been reported in nitrifying BAFs.¹⁵ The high influent solids concentrations may have caused some inhibition to

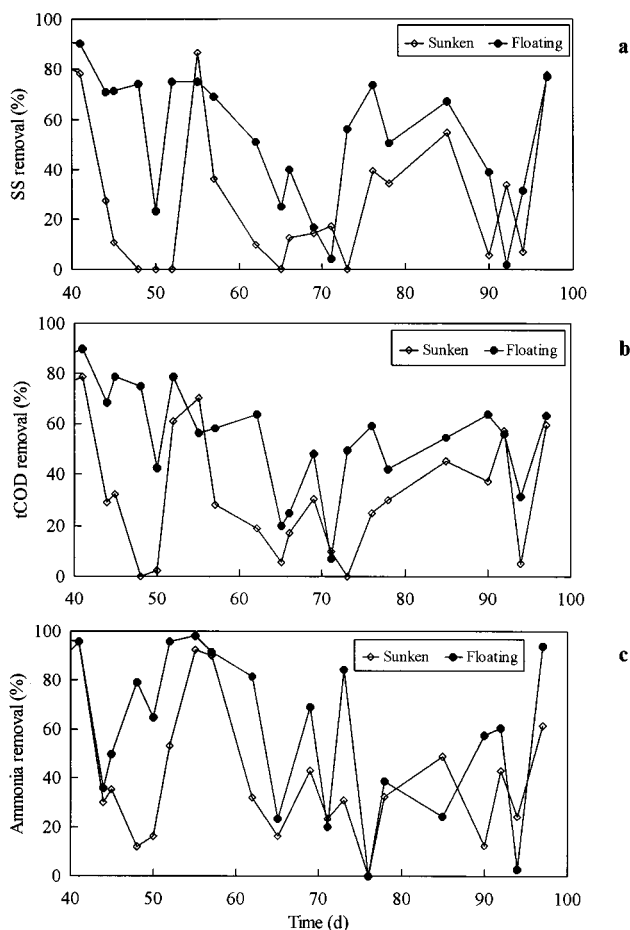


Fig. 3. Suspended solids (a), total COD (b) and ammonia (c) removal in sunken and floating media during temperature variations.

nitrifier growth. Concentrations of COD have been found to inhibit nitrification if limited or in excess.²² If limited, there will be an insufficient carbon source for biofilm growth. If in excess, the nutrients will promote rapid growth of carbonaceous-removing bacteria in preference to slow-growing nitrifiers.^{15,23,24} During the experimental period sCOD remained below 64 mg dm^{-3} with mean values of 46 mg dm^{-3} during start-up and 51 mg dm^{-3} during shock loading (Table 1). Generally, only partial sCOD removal rates of 20–30% have been found in tertiary (BAFs with 90% ammonia removal^{11,15} In the present experiments, 34% and 46% sCOD removal was reached for sunken and floating media, respectively. However, ammonia removal values of less than 62% were reached. The partial removal of the sCOD indicated that low sCOD concentrations did not inhibit performance. Solids concentrations in influent liquids have been found to inhibit performance in nitrifying reactors through absorption onto the biomass surface. This absorption causes thicker biofilms and inhibits the growth of nitrifiers. The high SS removal rates promoted the growth of carbonaceous-removing biofilms which further inhibit the growth of nitrifiers.¹⁶ Low concentrations of ammonia inhibit the start-up and performance of reactors through nutrient limitations. Indicated in the early stages of these experiments, higher loadings of ammonia promoted the growth of nitrifiers and subsequently improved nitrification rates.¹² A correlation between ammonia loading and removal rate was expected (Fig. 4) but the variation in temperature and in reactor performance did not allow for it.

The impact of temperature on the tCOD and ammonia removal was investigated (Fig. 5). During the experimentation period, the influent temperature ranged from 3.4 to 10.2°C. There appeared to be little direct relationship between temperature and tCOD removed (Fig. 5(a)). Overall, the floating medium appeared to have performed better than the sunken medium with removal rates as high as 80% at temperatures of 3.3°C. Ammonia removal showed a better correlation with temperature (Fig. 5(b)). Below 5°C, more than 60% removal was achieved, but at 10°C almost full nitrifica-

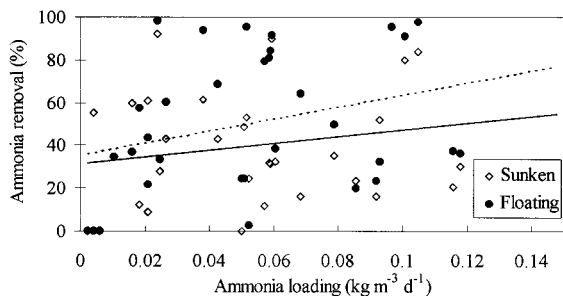


Fig. 4. Effect of ammonia loading on ammonia removal in sunken and floating media.

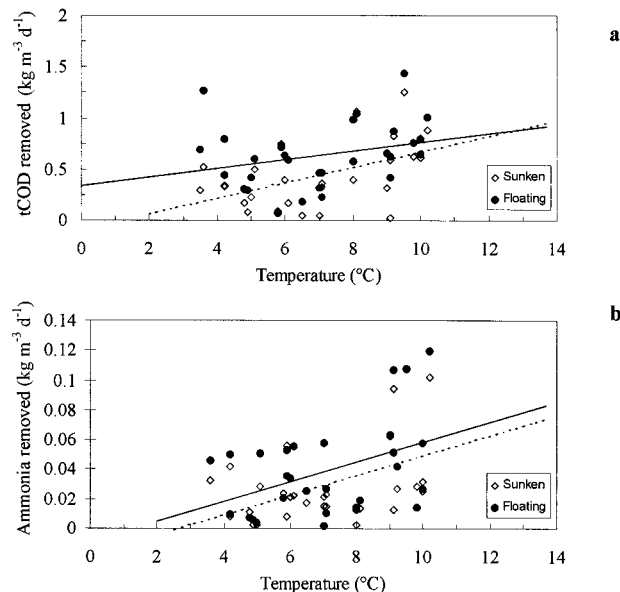


Fig. 5. Effect of temperature on total COD (a) and ammonia (b) removed.

tion was obtained, reaching a maximum removal rate of $0.121 \text{ kg m}^{-3} \text{ day}^{-1}$ for the floating medium and $0.105 \text{ kg m}^{-3} \text{ day}^{-1}$ for the sunken medium. Again the floating medium performed better than the sunken medium. From the results it appeared that nitrification would cease at between 1.5 and 2°C. Temperature has been found to have a great effect on biological reactor performance with up to 2% variation in nitrification performance occurring for every 1°C change in temperature.⁸ Though generally this is the case, BAF reactors have been found to perform well at variable temperatures.¹⁰

Overall the floating medium performed better than the sunken medium for SS, tCOD and ammonia removal. Tracer studies undertaken with clean water suggested that floating media would perform better than sunken media for solids removal due to much lower mixing.³ Therefore, it appears that high SS wastewater (such as the secondary effluent used in this study), would be best treated using floating medium upflow reactors. By running the floating medium reactor upwards, the traditional gravity type filter was reversed. Therefore, the liquid flowed in the direction of grain compression, enhancing solids retention. Further work on BAFs is being undertaken to confirm the greater capability of the floating media at removing SS.

Backwashing frequency appeared to be a major influence on reactor performance. In fixed-film reactors using structured media biofilm, biomass gradients are produced with high concentrations at the inlet, decreasing towards the outlet as nutrient concentrations drop.²⁵ In granular media reactors backwashing and backwashing frequency causes redistribution of biofilm

producing a more even distribution throughout the reactor.^{26,27} Initial backwashing on day 44 caused a rapid increase in ammonia removal without a subsequent increase in effluent nitrate concentrations (data not shown). Thus, ammonia nitrogen was not oxidised but used for biomass assimilation.^{18,19} This continued until day 55. At this point there appeared to be limited ammonia assimilation and a drop in ammonia removal efficiency (Fig. 3(c)). Hence, during initial start-up regular backwashing promoted biofilm growth. Following the build up of the biofilm, regular backwashing inhibited the performance of the reactors and should be carried out only where a decline in nutrient or SS removal is seen. Subsequently the net withdrawal of biomass from the system was greater than the net growth rate of the nitrifying bacteria. Thus backwashing should be restricted to avoid washout. Although fixed-film processes tend to be stable under shock loads,⁴ during the experimental period the process appeared to be unstable through over backwashing.

Unlike BOD removal which is a first order reaction, nitrification is a zero order reaction and thus independent of nutrient (ammonia) concentration.²⁸ Other factors such as high BOD can influence the order of reaction, making the nitrification zero order reaction into a half or first order reaction.²⁸ Previous investigations in upflow BAFs have found zero order type reactions at the bottom of the reactors while first order reactions occur at the top.¹⁸ Towards the end of the shock loading phase, bed profiles were carried out, which measured ammonia concentration at different heights along the length of the reactors and thus at increasing treatment times (Fig. 6). The profiles seem to indicate a zero or half order reaction and the carbonaceous matter appears to be the limiting factor. In order to confirm the type of reaction, the results were treated as both zero order (Fig. 7(a)) and half order (Fig. 7(b)). Both graphs showed a good correlation and followed a linear trend. Thus, the rate order of the reaction could not be confirmed. By using the operational flowrate ($3.3 \times 10^{-3} \text{ dm}^3 \text{ s}^{-1}$), the reactor height was transformed into units of time (s) in order to calculate the removal rates (Table 2). Both zero order and half order reaction kinetics confirmed the greater rate of ammonia removal in the floating medium than in the sunken

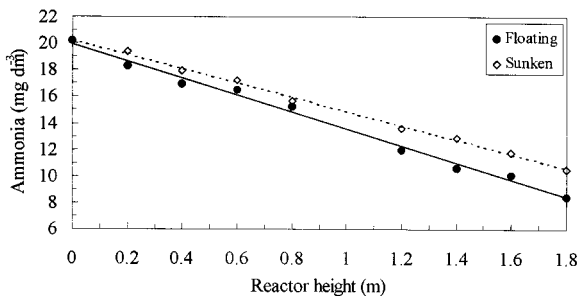


Fig. 6. Ammonia profiles for sunken and floating media.

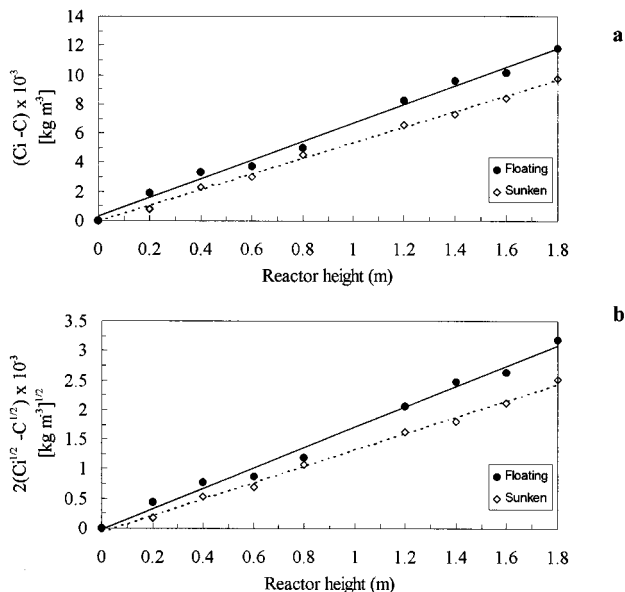


Fig. 7. Zero order (a) and half order (b) ammonia profiles for sunken and floating media.

medium. The results from sunken and floating media compare favourably to previous work on sunken media BAFs used for simultaneous carbonaceous matter and ammonia removal.⁹

4 CONCLUSIONS

Overall, floating media performed better than sunken media for SS, tCOD and ammonia removal, probably due to the compression of the bed due to the buoyancy force of the media and the flow of air and liquid acting upwards. Bed compression improved solids removal and appeared to have promoted the growth of bacteria. Temperature had a greater impact on nitrification than on carbonaceous matter removal. The floating medium reactor was more resistant to low temperature shocks than the sunken medium reactor but the latter showed a faster recovery time as temperature increased. Although the backwashing frequency used was satisfactory, performance may have improved if the backwashing had been carried out only when reactor performance began to decline. Nitrification was shown to follow a reaction rate between zero and half order. Thus, ammonia removal was generally independent of

TABLE 2
Removal Rates ($\times 10^{-6}$) for Nitrification

	Sunken Medium	Floating Medium
Iida and Teranishi (1984) ⁹ ($\text{kg m}^{-3} \text{ s}^{-1}$)	0.35–1.6	—
This study (zero order) ($\text{kg m}^{-3} \text{ s}^{-1}$)	1.38	1.54
This study (half order) ($(\text{kg m}^{-3})^{0.5} \text{ s}^{-1}$)	0.36	0.44

ammonia concentration and more affected by the presence of carbonaceous matter.

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