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Article

Performance of a Lab-Scale Closed Seawater Recirculating System for Korean Rockfish *Sebastes schlegeli* Culture

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Abstract : Performance of a laboratory scale closed seawater recirculating aquaculture system was evaluated. Twenty-kg of Korean rockfish (130 fish) with an average body weight of 153.8 g was stocked. Over a 107-day culture period, fish reached final density of 51.7 kg/m^3 (initial density, 33.3 kg/m^3) on the basis of the culture tank volume. On a daily basis, added water amounted to 3.4% of the total water volume in the system. Total ammonia nitrogen (TAN) concentrations were below 1 mg/*l* and nitrite nitrogen (NO_2-N) concentrations were within the range of 1-3 mg/*l* on most sampling days. TAN was removed from bead and sand filters and it was removed or produced in the sedimentation basin. Basically, NO_2-N was removed in the bead and sand filters, while it was either removed or produced in the sedimentation basin. Nitrate nitrogen (NO_3-N) was produced in the bead filters and removed from the sand filter and sedimentation basin. The foam fractionator performed well in the recirculating system. The maximal daily removal values for total suspended solids (TSS) and protein were 10.9 g and 1.4 g, respectively. Whole water quality parameters were within the levels commonly recommended for fish culture on most of the sampling days. However, further studies are needed to evaluate the commercial feasibility of this system because of the small-scale system used in present experiment. At least, the present study still provides some basic information for further studies of this kind of system.

Key words : recirculating aquaculture system, nitrification, denitrification, Korean rockfish

1. Introduction

It is widely acknowledged that fish supplies from the world fisheries are unlikely to increase substantially and that the expansion of the aquaculture sector will probably provide the solution to the problem of projected shortfalls (Chamberlain and Rosenthal 1995). As compared with the traditional fish culture methods, recirculating aquaculture systems consume less water and are operated with less effluent discharge (Shnel *et al.* 2002). However, common recirculating aquaculture systems still exert environmental impacts when considering the high solid and inorganic nitrogen contents in their effluents. More efficient treatment of waste generated within the recirculating system can reduce the environmental impact. Recently, zero-discharge closed recirculating systems were developed by Shnel *et al.* (2002) and Barak *et al.* (2003).

A laboratory scale closed seawater recirculating system designed based on the existing information for culture of Korean rockfish, *Sebastes schlegeli*, which is commercially important in Korea, has been developed. The principal compartments of the recirculating system include: a sedimentation basin and a foam fractionator for solids removal; styrofoam bead filters for TAN and NO_2-N removal; a sand filter for nitrate removal; a circular tank for fish culture; air blowers for aeration; and a heating system to prevent temperatures from dropping to excessively low levels. The water quality parameters in the culture tank water, the nitrification, denitrification and solids removal capacity in different treatment compartments, as well as

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fish growth are presented. Also, the performance of the whole system is evaluated.

2. Materials and methods

System configuration

Schematic diagram of the designed system is shown in Fig. 1. This system consisted of a 0.75 m^3 circular culture tank (water volume, 0.6 m^3), two nitrification bead filters, a denitrification sand filter, a sedimentation basin, a foam fractionator, a main water sump, and pumps. Sodium bicarbonate solution was supplied for pH compensation. Characteristics of the system compartments are shown in Table 1. For detailed information refer to Peng (2003).

Experimental procedure

This whole system was conditioned for 2 months before stocking by continuously feeding synthetic wastewater. For nitrification styrofoam bead filters, synthetic wastewater containing ammonia chloride and glucose was supplied to the culture tank to stimulate nitrification. The TAN concentrations were maintained at around 2 mg/*l* and COD concentrations were maintained at around 15 mg/*l* in the culture tank. Sodium nitrate and acetic acid were added to the sedimentation basin to stimulate denitrification. At this period, the sedimentation basin was separated from the system. The NO_3-N concentrations and organic matter concentrations were maintained at various C/N ratios for another set of experiments. Twenty-kg Korean rockfish (130 fish) with an average fish weight of 153.8 g were stocked in the culture tank on November 13, 2002. The styrofoam bead filters were backwashed once or twice daily at 0900 and/or 1700 h with a stirrer. The backwashing water flew back to the sedimentation basin. The whole system was operated on a closed mode without discharge of wastewater out of the system (or so called 'zero-discharge system'). Also, in order to obtain a better treatment effect, the water flow rates between each treatment apartment varied during the experimental period. The water temperature was maintained within the range of 16-19°C by a thermostatic heating system. All the fish were harvested on February 28, 2003.

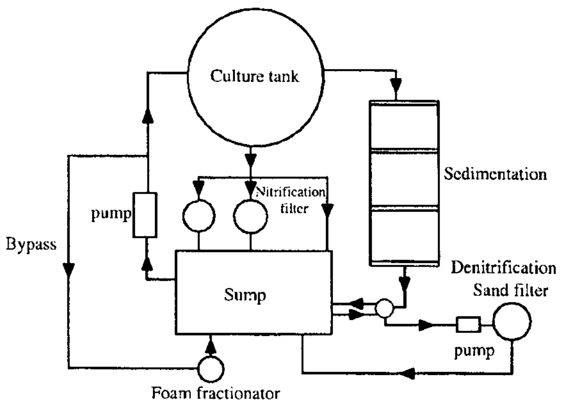

Fig. 1. Schematic diagram of the closed seawater recirculating aquaculture system. Arrows indicate the direction of water flow (not to scale).

Table 1. Characteristics of the compartments of the closed seawater recirculating system.

Compartment	Water volume (L)	Flow rate (L/h)	HRT (h)
Culture tank	600	1,200	0.5
Bead filter	50	450	-
Sedimentation basin	210	60-120	1.7-3.5
Sand filter	25	3-60	0.5-8
Water sump	120	-	-
Foam fractionator	30	1,200	-

Feed composition, feeding, and fish growth

Commercial formulated feed (Purina, Korea) was used. The main diet compositions were as follows: 40% protein; 10% fat; 18% ash; 1% calcium; 0.8% phosphorus; 2.3% moisture. Fish were fed at 9 am and 5 pm, 7 days a week, by hand. The daily feeding rate was around 1-1.5% of total fish weight. Fish growth was determined by monthly-interval weight determination over the experimental period. Any dead fish, if found, were taken out and weighed.

Sampling and analysis

Water samples were taken once every 3 days after the first feeding (around 10 am) from the inlet and the outlet water of each compartment. Also, foam condensates and culture tank water were sampled and analyzed. TAN (total ammonia nitrogen), NO_2-N (nitrite nitrogen), NO_3-N (nitrate nitrogen), and PO_4-P (reactive phosphorus) were measured using the methods described by Strickland and Parsons (1972). DO was measured with DO meter (KDO 5151, KRK Co.) and pH was measured with pH meter (Oregon, model 720 A). Total alkalinity was measured by the titration method (Grasshoff *et al.* 1999). Protein analysis was conducted according to Lowry *et al.* (1951). TSS was measured according to APHA (1995) and the filter paper was rinsed successfully 6 times with distilled water.

3. Results

Water quality parameters

During the experimental period, pH values fluctuated between 7.3-7.9 (Fig. 2). A relatively sharp drop of pH was experienced in the first 2 months, so a sodium bicarbonate solution was added to the system twice a week to prevent pH from dropping to excessively low levels. Then, the pH decreased at low rates and a sodium bicarbonate solution was added randomly whenever the pH values were found below 7.6. The decreased demands of sodium bicarbonate for maintaining pH levels higher than 7.6 were due to the elevated pH values in the outlet water of the sedimentation basin and sand filter. DO concentrations in culture tank water were maintained above 5.5 mg/*l* during the experimental period (Fig. 2). Temperatures fluctuated between 16.3 and 19.2°C.

Fig. 3 shows the changes of TAN, NO_2-N, NO_3-N and PO_4-P concentrations during the experimental period. TAN concentrations were below 1 mg/*l* in the first 2 months and showed a declining trend. However, TAN concentrations increased thereafter to around 1 mg/*l*. Nitrite nitrogen concentrations were within the range of 1-2 mg/*l* on most sampling days, while NO_3-N concentrations increased constantly within the first month and then fluctuated around 45 mg/*l*. Phosphate (PO_4-P) increased to around 31 mg/*l* and then fluctuated between 25-31 mg/*l* thereafter.

The differences between inlet and outlet TAN concentrations in the various treatment compartments through the experimental period are showed in Fig. 4. It can be seen that TAN was removed from the bead filters and sand filter. TAN was removed in the sedimentation basin in the initial experimental period, but was produced thereafter, especially in the last several weeks. Removal of NO_2-N was found in sand filters during the experimental period (Fig. 5). Basically, NO_2-N was removed in bead filters, while it was either removed or produced in the sedimentation basin. Nitrate nitrogen was produced in bead filters and removed from sand filters and the sedimentation basin (Fig. 6). A relatively high NO_3-N removal rate was found in sand filters in the last experimental period.

Diurnal change of TAN and NO_2-N in culture tank water

Diurnal changes in TAN and NO_2-N concentrations in culture tank water were depicted in Fig. 7. A dramatic fluctuation in TAN concentrations was noted, reaching the

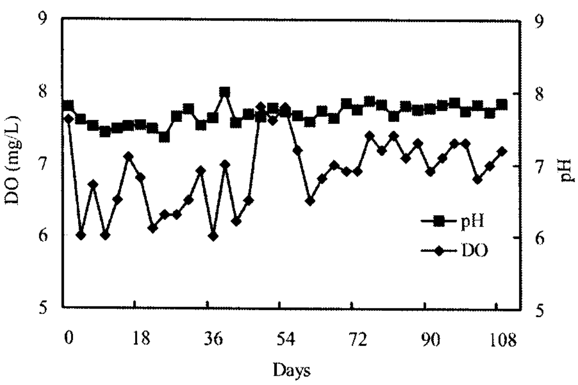

Fig. 2. Changes in DO concentrations and pH values in culture tank water during the experimental period.

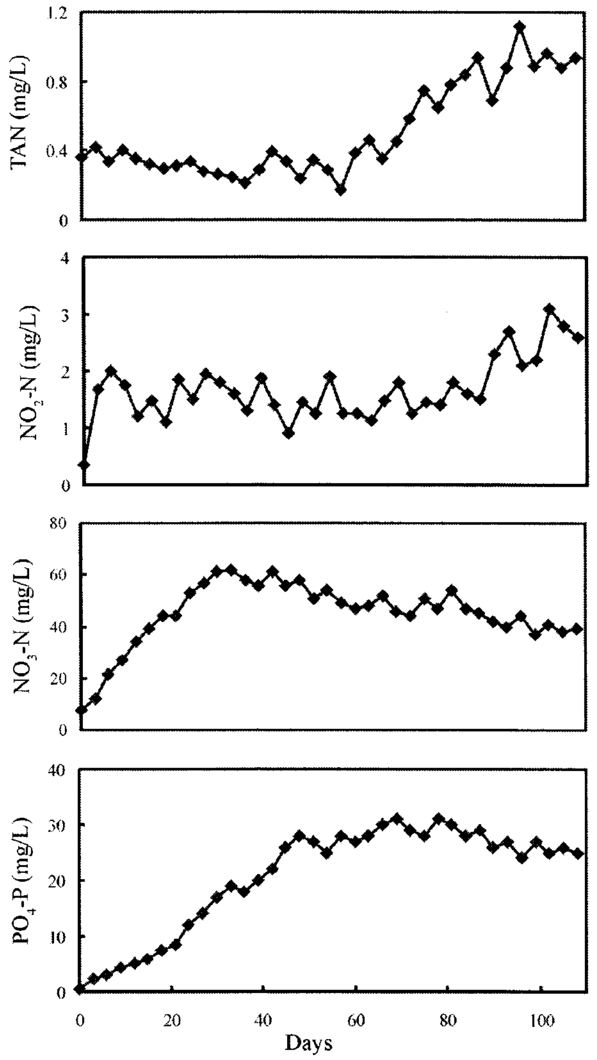

Fig. 3. Changes in TAN, NO_2-N, NO_3-N, and PO_4-P concentrations in culture tank water during the experimental period.

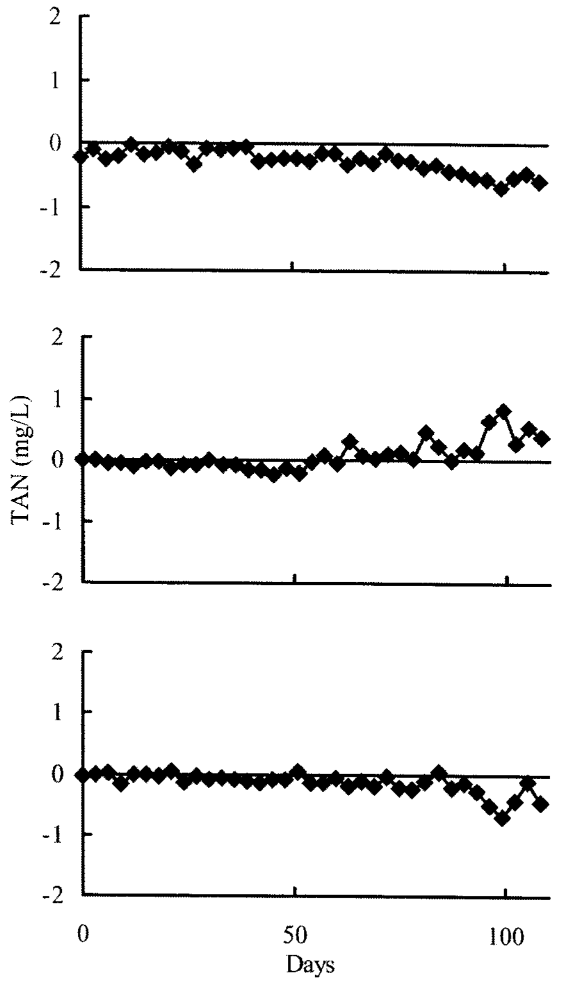

Fig. 4. Average production (positive values) and removal (negative values) of TAN in the different treatment compartments (Upper, styrofoam bead filters; Middle, sedimentation basin; Lower, sand filter).

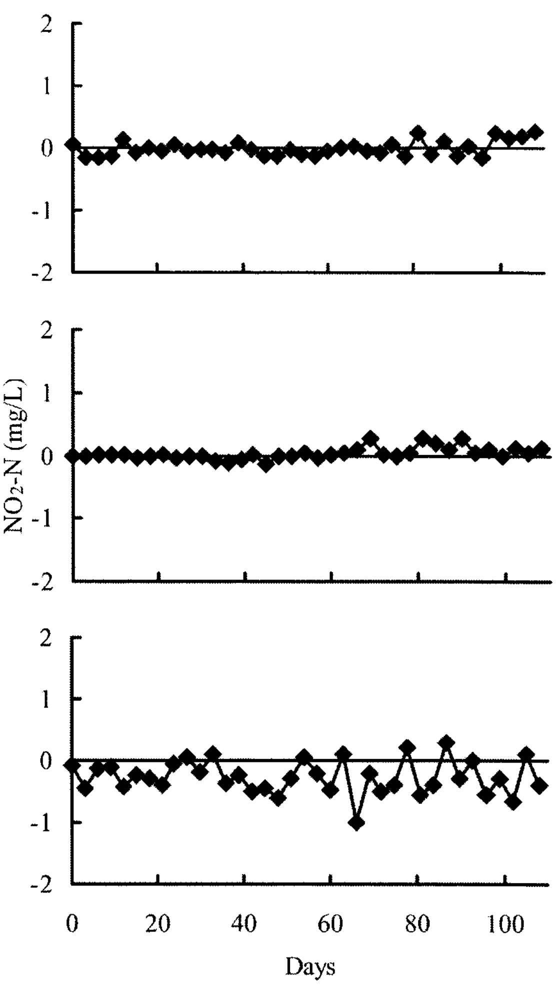

Fig. 5. Average production (positive values) and removal (negative values) of NO_2-N in the different treatment compartments (Upper, styrofoam bead filters; Middle, sedimentation basin; Lower, sand filter).

highest levels at around 4 hours after feeding. NO_2-N concentrations also increased following feeding and slight accumulations of NO_2-N were noted.

Fish growth performance and water requirement

Table 2 summarized the main growth characteristics of the Korean rockfish *Sebastes schlegeli* over a 107-day culture period. During this period, initial density was 33.3 kg/m^3 and final density was 51.7 kg/m^3 when calculated on the basis of culture tank volume. On the basis of the whole water system, the initial density was 18 kg/m^3 and the final density 28.2 kg/m^3. Average daily feed addition over the experimental period was 247 g with a maximum addition of 340 g (Fig. 8). The overall feed conversion ratio (FCR) was 2.4 and the survival rate was 90.7%.

Water losses in the system were caused by evaporation, losses associated with fish weighing and disease treatment procedures and flushing of the dual drain system. On a daily basis, added water amounted to 3.4% of the total water volume in the system. The water requirement was 373 liters for production of 1 kg fish and this value was high.

Nitrification characteristics of bead filters

DO concentrations in the inlet and outlet water fluctuated within the ranges of 5.5-8.3 and 3.2-5.4 mg/*l*, respectively. Mean and standard deviations were 6.81 ± 0.62 and 4.21 ± 0.59 mg/*l* in the inlet and outlet water, respectively.

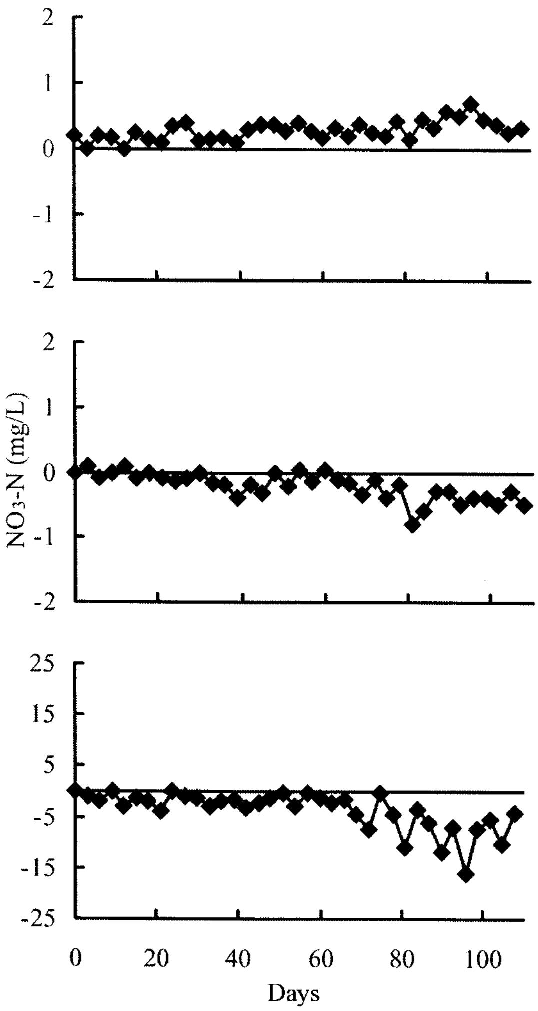

Fig. 6. Averaged production (positive values) and removal (negative values) of NO_3-N in the different treatment compartments (Upper, styrofoam bead filters; Middle, sedimentation basin; Lower, sand filter).

Table 2. Performance parameters of the closed seawater recirculating system.

Parameters	Value
Growth period (days)	107
Initial average fish weight (g)	153.8
Final average fish weight (g)	263
Total biomass increase (kg)	11
FCR	2.4
Survival (%)	90.7
Average daily water exchange (% of total water volume)	3.4
Specific water consumption (*l*/kg fish produced)	373

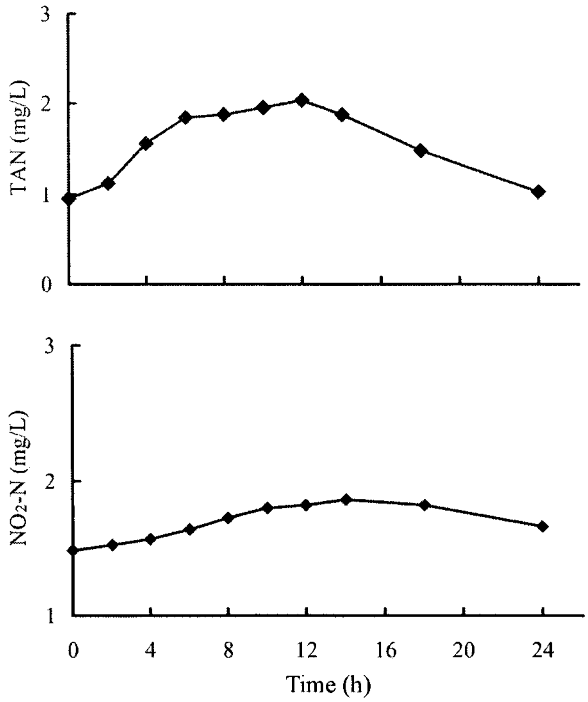

Fig. 7. Diurnal change of TAN and NO_2-N concentrations in culture tank water measured on day 87.

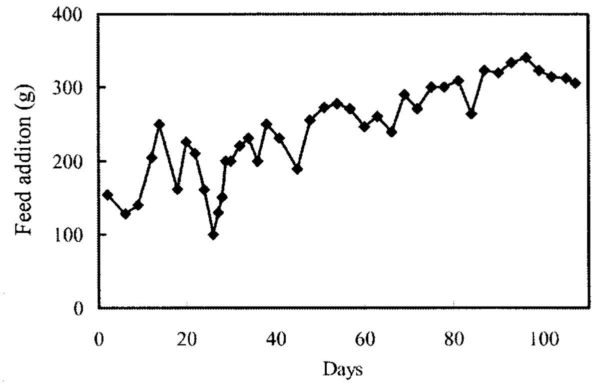

Fig. 8. Average daily feed input to the experimental system during the experimental period.

TAN conversion rate increased in the styrofoam bead filters with an increase of inlet TAN concentrations (Fig. 9). The data presented in this figure were collected during the experimental period, which means that temperature, pH, and other water quality parameters fluctuated. TAN concentrations in the inlet water for most sampling days during the experimental periods did not exceed 2 mg/*l*. Therefore, the maximum conversion rates were not obtained as they occurred at higher inlet TAN concentrations as found in previous experiments (Peng 2003). Areal TAN

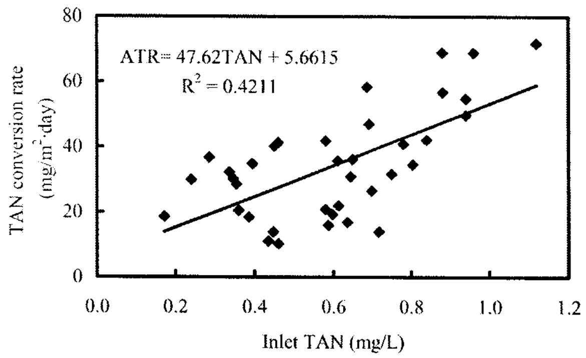

Fig. 9. TAN conversion rates of styrofoam bead filters at various inlet TAN concentrations in the closed seawater recirculating system.

Table 3. Foam overflow rate (FOR) and daily removal of TSS and protein by foam fractionator at different superficial air velocities (SAV) of 0.743, 1.114, and 1.486 cm/sec, and foam overflow heights (FOH) of 1, 3, 5, and 7 cm.

SAV (cm/sec)	FOH (cm)	TSS (g/day)	Protein (g/day)	FOR (mL/min)
0.743	1-7	5.7-1.3	0.9-0.2	6.8-0.6
1.114	1-7	7.1-1.8	1.5-0.4	9.2-1.6
1.486	1-7	11-2.2	2.8-0.6	36.2-2.5

conversion rates (ATR) can be described as:

$$ATR = 47.62TAN + 5.6615 \ (R^2=0.4211).$$

Performance of foam fractionator

Table 3 summarizes foam overflow rates, daily removal of TSS and protein by a foam fractionator. The daily removal amount was calculated by multiplying the variable concentrations with the volume of foam condensates collected. Daily removal of TSS and protein for various treatments were within the ranges of 1.3-11 and 0.4-2.8 g, respectively. The daily removal amounts and foam overflow rates increased with the increase of superficial air velocities, but decreased with the increase of foam overflow heights. Concentrations of TSS and protein concentrations were higher in foam condensates collected for higher foam overflow height treatments, but the foam overflow rates decreased with an increase in the foam overflow height. Daily removals of these variables were greatly affected by the foam overflow rates. Lower foam overflow height resulted in greater removal of these variables when compared with high foam overflow height treatments. Daily removals of TAN, NO_2-N, NO_3-N and PO_4-P were not shown here due to the low values calculated and this showed that the low efficiency of foam fractionators for reduction of these variables.

4. Discussion

This study was to present the performance data, with respect to growth performance and water quality of an intensive seawater recirculating system. The main purpose aimed at demonstrating the technical feasibility of a Korean rockfish culture in an almost completely closed mode and reasonable results were obtained. However, further studies are needed to evaluate the commercial feasibility of this kind of system because a small-scale system was used in the present experiment. Nevertheless, the present study still provides some basic information for further studies of this kind of system.

Water quality

The whole water quality parameters were within the levels commonly recommended for fish culture on most of the sampling days, except in the case of the relatively high nitrite concentrations encountered. Fortunately, nitrite is not so toxic in seawater as that in freshwater since chloride ions can increase the tolerance of fish to nitrite by a factor of 20 to 60 times (Wedemeyer and Yasutake 1978). Since water samples were collected just after the first feeding, the depicted TAN concentrations did not represent the maximum concentrations in the culture system. The diurnal changes of TAN concentrations measured on day 87 (Fig. 7) showed that maximum concentrations exceeded 2 mg/*l*. This indicates that the system was already operated at maximum feed load or nearly the maximum carrying capacity. Increasing the hydraulic loading rates through the nitrifying bead filter could possibly improve the nitrification performance in styrofoam bead filters and thus decrease the TAN concentrations in culture tank water (Greiner and Timmons 1998; Nijhof and Klapwijk 1995; Shnel *et al.* 2002). However, this could increase the NO_2-N concentrations in the culture tank water as found in the previous study, so no attempts have been made in this regard. On the other hand, production of TAN in the sedimentation basin contributed to the elevated TAN concentrations in the last experimental period. This presents another question in designing a recirculating system, taking into account that TAN production should be a necessity whenever the sedimentation basin is used for digestion purposes, especially for closed zero-discharge aquaculture systems as used in present experiment. However, no detailed information about TAN production in the sedimentation basin was provided till now and quantification of this TAN production needs further study.

High NO_2-N concentrations in the culture tank water was partially due to the possible production of NO_2-N in bead filters at high inlet TAN concentrations and partially due to the production of NO_2-N in the sedimentation basin, especially in the last experimental period.

Though fish are poorly utilizing phosphorus in feed (Avnimelech and Lacher 1979; Schroeder *et al.* 1991; Green and Boyd 1995), decline of phosphate concentrations in culture tank water indicates that phosphorus should have been reduced in the treatment compartments. Shnel *et al.* (2002) reported that phosphate was reduced in the digestion basin and denitrification biofilter. Barak and van Rijn (2000a) found that denitrifiers were capable of phosphate uptake in excess of their metabolic requirements and phosphate removal from water in the experiment system was mainly mediated by denitrifying organisms. Studies on a number of denitrifier isolates (Barak and van Rijn 2000b, c) further confirmed their findings. This would explain the phenomena in the present experiment considering the similarity of the systems used.

Growth performance

Fish growth was lower than expected. The main reason should be the disease encountered during the experimental period. Fish were found to be heavily infested with parasites and possibly bacteria. They were treated with formalin and antibiotics. Davis and Arnold (1998) demonstrated that the primary disease observed in a shrimp production system was generally associated with poor water quality and/or stress due to crowding. Funge-Smith and Briggs (1994) also concluded that accumulation of organic matter, together with the other stressful situations, often leads to outbreaks of disease. The accumulation of organic matter in the sedimentation basin in the present system along with the occasional higher TAN concentrations and other stressful factors would have contributed to the outbreak of disease. However, detailed research would be required to clear this. The feed conversion ratio was relatively high when compared with the common values reported.

Nitrification characteristics of bead filters

The measured maximum TAN conversion rate in the styrofoam bead filters was 72 $mg/m^2 \cdot day$. Higher TAN conversion rates could probably be obtained at higher inlet TAN concentrations as found in the previous study (Peng 2003), TAN conversion rates increase with an increase of inlet TAN concentrations. TAN conversion rates were lower than those obtained in previous experiments when compared on an equal basis to inlet TAN concentrations. The differences could be easily recognized by comparing the equation obtained by plotting the TAN conversion rates versus inlet TAN concentrations obtained in present experiments with those obtained in previous studies (Peng *et al.* 2003). Solids would affect TAN conversion rates. During the experimental period, backwashing once or twice daily is necessary to ease clogging problems or beads would be washed out of the biofilter column. Chitta (1993) observed in an experimental propeller-washed filter that the rate of TAN oxidation increased with a decrease in backwashing frequency, an aspect he attributed to the longer mean cell residence time. However, inhibition of nitrifiers may take place due to accumulation of organic solids and heterotrophic biomass. Malone *et al.* (1999) explained that organic loading inhibits spatial transport of nutrients to the nitrifying bacteria. TAN conversion rates showed large fluctuation when compared with those obtained in previous experiment and this indicated that nitrification could be affected largely by the operating factors of the system. Kamstra *et al.* (1998) also found a large fluctuation in trickling filters used on eel farms.

Performance of sedimentation basin and sand filter

Nitrate removal was found to occur in sedimentation basin. Since internal baffles were used, the organic matter was mainly accumulated in the inlet region of the basin. This may cause an uneven distribution of inorganic nutrients within the basin. Aboutboul *et al.* (1995) and Shnel *et al.* (2002) concluded that it is in this region where labile organic matter is degraded and volatile fatty acids are released and used for nitrate reduction by denitrifiers. The low organic matter in the sedimentation basin would have caused the low nitrate reduction at the beginning. Also, the short HRT also contributed to this low nitrate removal. Another important reason is that the time lag for developing anoxic conditions and heterotrophic bacteria within the basin. Later, the water flow rates through the sedimentation basin were further reduced and this increased nitrate removal.

Nitrate removal in the sand filter was lower than expected, especially in the first 2 months, though the filter already was conditioned for 2 months before being cooperated into the system. The main reason should be due to the low carbon sources to mediate the denitrification process. Since the water was pumped into the sand filter from the outlet of sedimentation basin, organic matter already was, at least partially, consumed in the sedimentation basin by the denitrification process. Alternatively, high inlet DO concentrations (3.5 ± 0.62) and short hydraulic retention time contributed to the poor performance of the sand filter. Decreased denitrification efficiencies due to low C/N ratio, short hydraulic residence time, and high inlet DO concentrations in denitrification biofilters have been reported by Lee (1993) and Oh *et al.* (1997).

The sand filter was initially designed to operate in a fluidized mode, but we later found this is not practical. Water flow rate was reduced to only 3-15 *l*/hour and this improved the performance. This can be evidenced by the elevated nitrate removal in the last experimental period. Alternatively, lowering the inlet DO concentrations by increasing the surface area of the sedimentation basin or hydraulic retention time may improve the performance of the sand filter. Nevertheless, the optimal operation parameters for the denitrification sand filter need further detailed research.

Overall, the combination of the sedimentation basin and the denitrification sand filter worked well for nitrate reduction. This combination eliminates the requirement of external carbon sources for denitrification. However, production of ammonia within the sedimentation basin, as mentioned in the previous part, would increase the volume of the nitrification biofilter.

Foam fractionator

Foam fractionation is not an effective way to achieve the removal of dissolved inorganic matter. Spotte (1979) already concluded that within the common pH ranges, foam fractionation does not reduce the level of ammonia in aquarium water. Hussenot *et al.* (1998) also found lower enrichment factors for TAN, NO_2-N, and NO_3-N in marine aquaculture systems. Results of TSS and protein removal indicates that using minimal overflow heights may produce foam condensate that may only be marginally more concentrated with variables than the culture water and high overflow heights may produce extremely concentrated foam condensates, but the foam production rate may be extremely low. One could select the operating factors to satisfy their desired result, by minimizing the wastewater volume or maximizing removal of variables in order to ensure good water quality for fish cultures.

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