J. Fish. Sci. Tech., 7(2), 76-83, 2004

JOURNAL OF
FISHERIES SCIENCE
AND TECHNOLOGY

Performance of a Recirculating Aquarium System for the Culture and Holding of Marine Fish

Lei Peng and Jae-Yoon Jo*

Department of Aquaculture, Pukyong National University, Busan 608-737, Korea

To supply fresh and quality quarantined seafood in live seafood specialty restaurants, facilities for short-term culture or holding of live marine fish and shellfish are a necessity. In this study, the performance of a simple recirculating aquarium system for the culture and holding of marine fish was evaluated. The aquarium system consisted of a culture tank, a foam fractionator for solids removal, and a Styrofoam bead filter for nitrification and solids trapping. In the first trial, the aquarium was stocked with a total of 12 kg Korean rockfish, which were fed approximately 0.5% of the total fish body weight daily. During the 2-month culture period, total ammonia nitrogen (TAN) and nitrite nitrogen (NO_2-N) concentrations remained below 1 mg/L and 2 mg/L, respectively. The chemical oxygen demand (COD) fluctuated between 13.6 and 31.2 mg/L on selected sampling days. The total suspended solids (TSS) removed by the foam fractionator was between 2.7 and 4.6 g daily. The Styrofoam bead filter not only reduced TAN and NO_2-N in the culture tank water, but also trapped solids equivalent to 8.3-26.7% of the weight of feed supplied. In Trial 2, 30 kg of live fish were held in the aquarium without feeding for a 24-hour period and the water quality parameters were monitored. TAN and NO_2-N concentrations first increased and then decreased to around 0.3 mg/L. These results demonstrate that the recirculating aquarium system is a functional option for the short-term culture or holding of marine fish.

Key words: Aquarium, TAN, Styrofoam bead filter, Korean rockfish, Foam fractionator

Introduction

Marine aquaculture has developed quickly over the last few decades in Korea, and increased consumption of live seafood has contributed, in part at least, to the speed of this development. To supply fresh and quality quarantined seafood in live seafood specialty restaurants, facilities for the short-term holding or culture of marine fish and shellfish have become a necessity. In coastal areas, where seawater is abundantly available, aquarium systems with a simple mechanical filtration mechanism are sufficient to maintain live fish, provided that periodic changes of water are maintained. However, in inland areas, recirculating aquarium systems offer a suitable means of overcoming the limited availability of seawater.

Recirculating aquarium systems for holding live fish usually consist of a culture or holding tank, a recirculating pump, a filter for removing solids and ammonia, and aerators to increase dissolved oxygen. Currently in Korea, a commonly used filter material consists of coarse sand mixed with shell debris. This filter material is believed to facilitate the removal of solids, as well as contribute to the maintenance of pH levels in the aquarium system. Some new materials, such as loess beads and Styrofoam beads, have also been developed and introduced into aquarium systems. However, the efficacy of these new materials in functioning aquarium systems has not been evaluated. We previously tested the nitrification efficiencies of Styrofoam beads in simulated freshwater and seawater aquaculture systems; the results indicated that they were very suitable for the removal of ammonia and capture of solids (Peng et al., 2003; Peng and Jo, 2003a). In addition, in a comparison of the nitrification and organic matter removal capacities of sands, loess beads and Styrofoam beads in a simulated seawater aquaculture system, Peng et al. (2003) demonstrated that the nitrification rates of Styrofoam beads were 3- to 8-fold higher than those of loess beads and sands. The superior nitrifica-

---

*Corresponding author: jhjo@pknu.ac.kr

tion and solids capture capabilities of Styrofoam beads indicated that they could be used as filter media in simple and compact aquarium systems. In addition, Styrofoam beads are very inexpensive and are easily handled, due to their low specific gravity.

In a restaurant setting, the transparency of the water in an aquarium system is of crucial importance, as customers are able to observe the tanks and their contents; the clarity of the water affects customers' opinions about the quality of the fish. Closed aquarium systems are subject to an accumulation of fine suspended solids and dissolved organics when periodic water changes are not practicable (Timmons et al., 1995). Many technologies have been developed for the removal of solids in aquaculture systems, including sedimentation basins, microscreens, hydrocyclones and foam fractionators (Henderson and Bromage, 1988; Makinen et al., 1988; Chen et al., 1993a, b). Use of these systems, other than foam fractionators, for the mechanical removal of solids is usually considered to be unnecessary in small-scale aquarium systems, providing the biofilters are capable of trapping solids. Moreover, these systems for the mechanical removal of solids are usually expensive to operate in small aquarium systems.

Chen et al. (1993c) found that 95% of the suspended solids in recirculating aquaculture systems had a diameter less than 20 μm, and that these finer suspended solids cause the most serious problems in closed systems. The majority of the fine particles remain even after passing through biofilters (Muir, 1978). Foam fractionators have been found to be very effective in removing solids from aquarium water, especially fine solids (Weeks et al., 1992; Chen et al., 1993a, b; Chen et al., 1994; Suh et al., 2000, 2002; Peng and Jo, 2003b). Thus, the combination of a nitrification biofilter with a foam fractionator is common in aquarium systems. Indeed, Lomax (1976) has found that, in terms of cost effectiveness, this combination offered the best design of several culture systems that were examined.

In the present study, the performance of a recirculating aquarium system, consisting of a culture tank, a foam fractionator, and a Styrofoam bead filter, was examined. In the first trial, fish were fed twice daily and the performance of the system for short-term culture in a closed mode was evaluated. This trial simulated the conditions common in inland areas, where seawater cannot be freely obtained, and frequent transportation of live fish is not practicable, due to high transportation fees. A second trial evaluated the performance of the system at a higher stocking density, without feeding, thus simulating the common practice of short-term holding, as used in live fish restaurants. The objective was to provide basic information about the performance of this newly developed, recirculating aquarium system.

Materials and Methods

Experimental system

The aquarium system consisted of a culture tank, a Styrofoam bead filter, a foam fractionator, a water sump, and a circulation pump (Fig. 1). Water from the tank overflowed to the foam fractionator, from which the outflow was directed partially to the Styrofoam bead filter and partially to the water sump. Aeration was supplied in the culture tank, and in the foam fractionator. The design criteria of the various components used in the aquarium system are shown in Table 1. The rectangular culture tank was 80×70×60 cm, with a capacity of 330 L and a normal fill volume of 280 L. The total volume of water in the system was approximately 360 L.

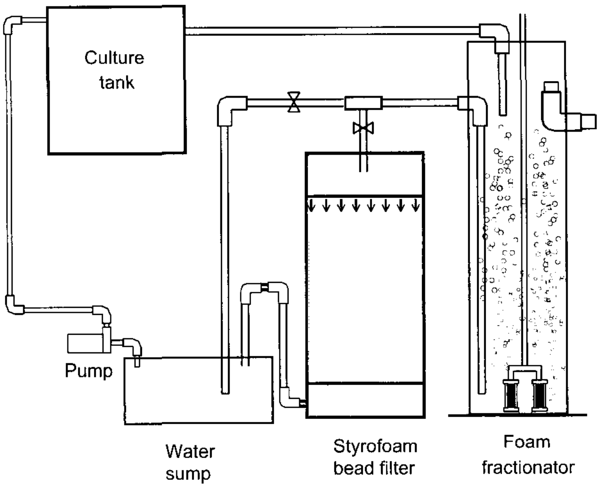

Fig. 1. Schematic diagram of the recirculating aquarium system (not to scale).

The biofilter column was polyvinyl chloride (PVC) pipe, 90 cm tall, and 20 cm in diameter. A grating was placed near the bottom of the column to retain the Styrofoam biofilter media and another at the top to ensure even distribution of inflow water. The flow rate through the Styrofoam bead filter was approximately 4.5 L/min. In total, 12 L of round, 1.4 mm average diameter, Styrofoam beads were used; the

Table 1. Design criteria for the components used in the recirculating aquarium system

Compartment	Volume (L)	Water volume (L)	Flow rate (L/min)	HRT (min)
Culture tank	330	280	40.0	7.0
Foam fractionator	38	33	25.0	1.3
Bead filter	28	18	4.5	4.0
Water sump	52	35	40.0	0.9

HRT, hydraulic retention time

calculated specific surface area was 2,820 m^2/m^3. The specific gravity of the beads was only 1/30 that of water; therefore, most of the beads in the biofilter tended to float on the surface of the water. No mechanical backwashing measures were adopted; a simple propeller made of PVC pipe and plate was used to manually backwash periodically. Backwashing was usually done once daily, but the frequency varied, according to the performance of the Styrofoam bead filter and the water quality in the whole system.

The foam fractionator column was acrylic pipe, 100 cm tall, and 15 cm in diameter. The inflow was at the top and the water outlet was near the bottom of the column, forming a counter-current flow pattern. The water flow rate was set at 25 L/min. Foam was collected via a 40-mm PVC elbow affixed at the 100-cm level, and the foam overflow height was set at approximately 3 cm. The air flow rate through the foam fractionator column was 20 L/min, using two air stones (3.2 cm in diameter, 9 cm long) to disperse bubbles.

Experimental procedure

The Styrofoam bead filter was conditioned for 6 weeks by feeding synthetic wastewater containing 139 g/L ammonia nitrogen (NH_4-N), 350 g/L $NaHCO_3$, 15.9 g/L Na_2HPO_4, 15.3 g/L KH_2PO_4, and 3.6 g/L $MnSO_4 \cdot 7H_2O$. Total ammonia nitrogen (TAN) concentrations in the inflow water were maintained at the desired concentration of approximately 2 mg/L TAN by changing the rate of addition of synthetic wastewater. The water temperature was maintained at 18°C with a thermostatic heating system.

The efficacy of the aquarium system for maintenance of water quality was evaluated in two conditions. In Trial 1, fish were maintained in the aquarium for two months under recirculating conditions. The tank was stocked with a total of 12 kg Korean rockfish, *Sebastes schlegeli*, with an average body weight of 300 g. The fish were fed twice daily, at 10 am and 5 pm, at a rate of approximately 0.5% of total body weight of the fish. A commercially available, formulated feed (Purina, Korea) was used, with the following composition: 40% protein; 10% fat; 18% ash; 1% calcium; 0.8% phosphorus.

In Trial 2, a total of 30 kg of live fish were stocked and held for 24 hours, during which the water quality parameters were monitored. To simulate the common practices used in live fish restaurants, the fish were not fed.

Sampling and analysis

In Trial 1, water samples were taken once every three days after stocking, at 11 am. Water samples were taken from the culture tank, and from the inlet and outlet of the Styrofoam bead filter. In Trial 2, the water samples were taken from the culture tank at 1-hour intervals for the first 6 hours after stocking, and at 2- to 4-hour intervals thereafter. TAN, nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), and chemical oxygen demand (COD) were measured, using the methods described by Strickland and Parsons (1972). Temperature and dissolved oxygen (DO) were measured using a DO meter (KDO 5151, KRK Co., Tokyo, Japan). Total alkalinity was measured by the titration method (Grasshoff et al., 1999) and pH was measured using a pH meter (Oregon model 720 A, Oregon, USA).

In Trial 1, the foam condensate and backwashing wastewater were collected and the volume was recorded. Total suspended solids (TSS) were measured using the APHA method (APHA, 1995). Samples were filtered and the filter paper was rinsed 6 times with distilled water to remove residual salts and determine the weight of the solids. The amounts of solids removed daily by the foam fractionator and the Styrofoam bead filter were calculated by multiplying the volume of the foam condensate or backwash water collected for the 24-h period by the corresponding solids content.

Results

Changes in water quality parameters in culture tank water

In Trial 1, DO concentrations in the culture tank water fluctuated between 7 and 7.8 mg/L, and pH values also fluctuated considerably (Fig. 2). Whenever the pH decreased to near 7.4, sodium bicarbonate solution was supplied to elevate the pH in the culture tank water. Changes in the concentrations of TAN, NO_2-N and NO_3-N are shown in Fig. 3. The concentration of TAN remained below 1 mg/L during the experimental period, while the concentration of NO_2-N increased at the beginning of the culture period and then decreased to below 1 mg/L. The concentration of NO_3-N increased steadily during the two-month experimental period, reaching 123 mg/L at the end of the experiment. Average total alkalinity concentration was 118 mg/L (data not shown). The COD fluctuated between 13.6 and 31.2 mg/L (Table 2) on the selected sampling days.

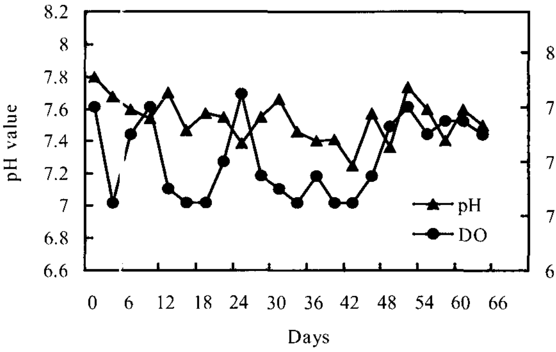

Fig. 2. Changes in concentration of pH and DO in culture tank water in the recirculating aquarium system in Trial 1.

Fluctuations in TAN and NO_2-N concentrations during the 24-hour holding period

In Trial 2, the concentration of TAN increased from near zero to about 0.7 mg/L 6 hours post-stocking, and decreased thereafter (Fig. 4). NO_2-N concentrations also increased after stocking, reaching peak concentrations of 1.32 mg/L approximately 10 hours post-stocking. TAN and NO_2-N concentrations decreased to 0.2 and 0.3 mg/L, respectively, 24 hours post-stocking.

Performance of the Styrofoam bead filter and foam fractionator

The data presented in Fig. 5 were collected during the two-month experimental period of Trial 1. The removal of TAN by the Styrofoam bead filter increased with increasing inlet TAN concentrations. However, during the experimental period, inlet TAN concentrations did not exceed 1 mg/L. Therefore, maximal TAN removal rates were not obtained, as they occur at higher concentrations. The maximum TAN removal rate (TAN_{Inlet} - TAN_{Outlet}) was 0.43 mg/L. Taking into account the average inlet water flow rate of 4.5 L/min, the total surface area, and the volume of Styrofoam beads used, the daily maximum removal rates, on the basis of surface area and volume of Styrofoam beads, were calculated to be 83.2 mg/m^2·day and 232.2 g/m^3·day, respectively. Nitrite nitrogen removal was influenced by TAN removal; NO_2-N removal increased with increasing TAN removal (Fig. 6), but the correlation is quite low ($r^2=0.68$). In addition, NO_2-N accumulated with

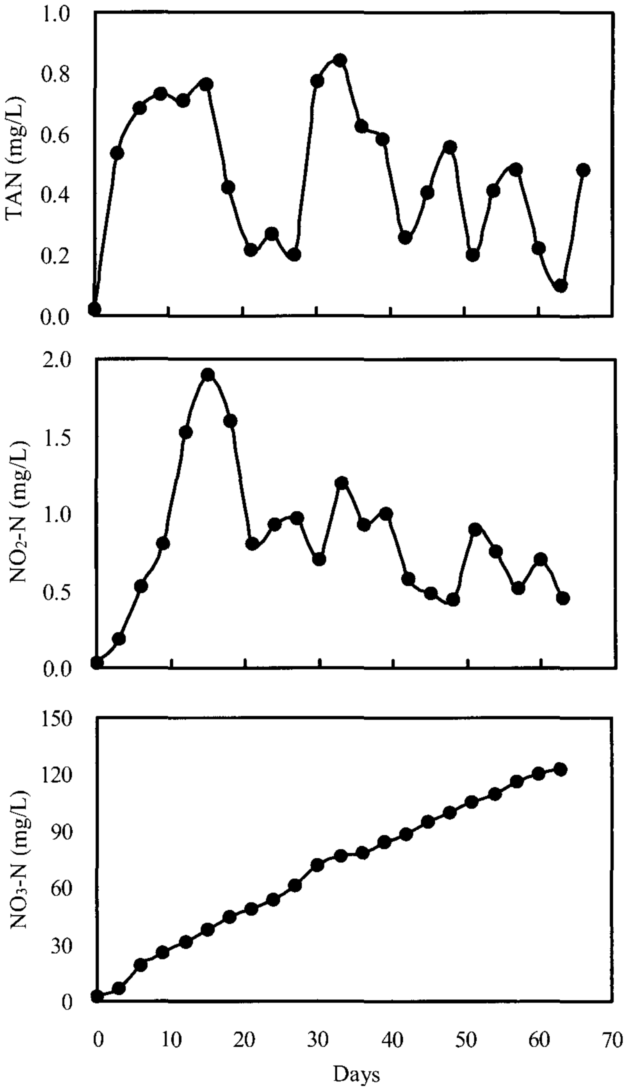

Fig. 3. Changes in concentration of TAN, NO_2-N and NO_3-N in the culture tank water in the recirculating aquarium system in Trial 1.

Table 2. Concentration of chemical oxygen demand (COD) in culture tank water, inlet water and outlet water of the Styrofoam bead filter and removal of COD (inlet-outlet) on selected sampling days

Sampling day	COD concentrations (mg/L)			
	Tank	Styrofoam bead filter		
		Inlet	Outlet	Difference
3	13.6	12.0	9.3	2.7
9	18.4	16.2	15.3	0.9
12	13.8	12.2	11.0	1.2
15	21.2	19.6	13.0	6.6
18	26.9	25.6	20.4	5.2
27	28.8	28.7	24.0	4.7
30	31.2	30.2	29.4	0.8
36	18.6	18.4	17.6	0.8
42	22.4	20.7	20.7	0.0
48	28.3	28.3	25.8	2.6
54	15.3	14.4	11.2	3.2
60	28.1	26.4	17.6	8.8

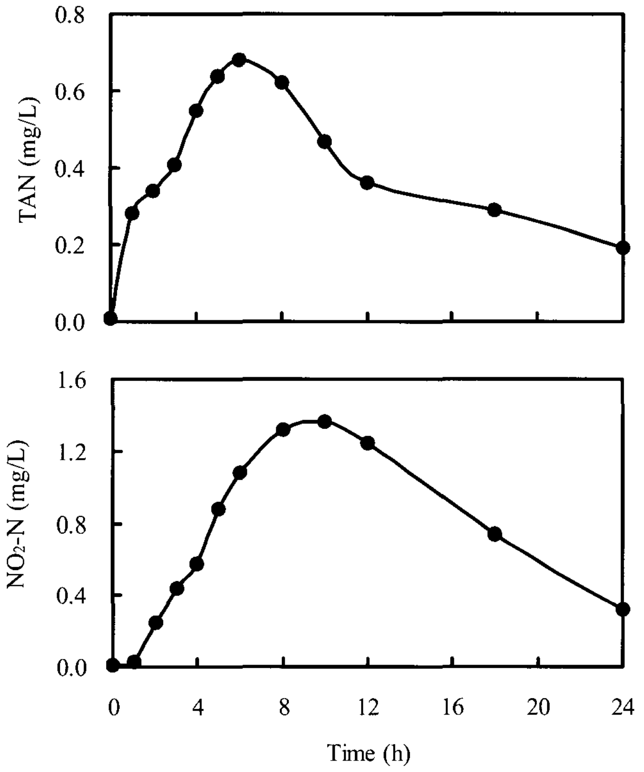

Fig. 4. Changes in concentration of TAN and NO_2-N in culture tank water over a 24-hour period in the recirculating aquarium system in Trial 2.

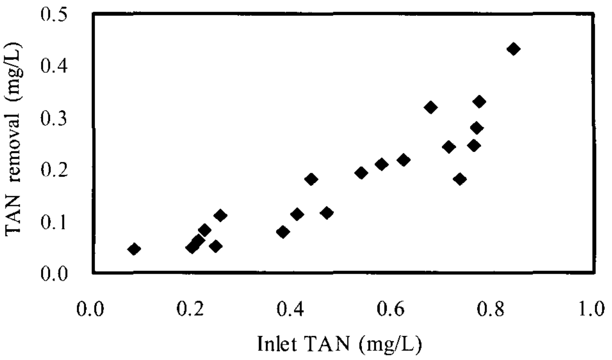

Fig. 5. TAN removal ($TAN_{inlet} - TAN_{outlet}$) by the Styrofoam bead filter at various inlet TAN concentrations in the recirculating aquarium system in Trial 1.

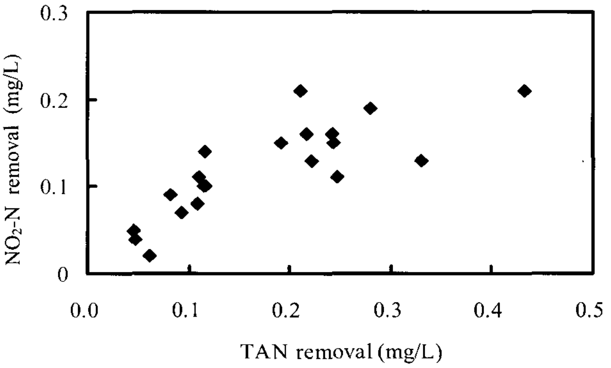

Fig. 6. Nitrite nitrogen removal (($TAN_{inlet} - TAN_{outlet}$) + ($NO_2\text{-}N_{inlet} - NO_2\text{-}N_{outlet}$)) versus TAN removal ($TAN_{inlet} - TAN_{outlet}$) by the Styrofoam bead filter in the recirculating aquarium system in Trial 1.

increasing TAN removal. Removal of COD by the Styrofoam bead filter also fluctuated significantly during the experimental period (Table 2), varying from 0 to 8.8 mg/L.

The performance data for the foam fractionator on selected sampling days are shown in Table 3. The volume of foam condensate produced varied during the experimental period, ranging from 4.7 to 9.6 L daily. Also, the concentration of TSS in the foam condensate and the daily removal of TSS ranged from 438 to 786 mg/L, and from 2.7 to 4.6 g/day, respectively.

Water requirement and fish performance

The volume of water required for daily backwashing of the Styrofoam bead filter was approximately 8 L. The concentration of TSS in the wastewater fluctuated considerably, ranging from several hundred to approximately one thousand mg/L (data not shown). Also, solids accumulated in the small water sump,

Table 3. Performance of the foam fractionator on selected sampling days

Sampling day	Volume (L)	TSS concentration (mg/L)	TSS removal (g/day)
Day 6	6.8	576	3.9
Day 17	4.7	786	3.7
Day 28	9.6	484	4.6
Day 41	6.2	438	2.7
Day 56	4.9	672	3.3

and cleaning 2-3 times per week was required to remove the sediments. This resulted in an additional 20-30 L in weekly water consumption. Another water loss was caused by the foam fractionator, ranging from several to 10 L. Consequently, the total weekly requirement for additional water was approximately 120 L.

The survival rate among the fish was 92.5% in Trial 1, despite the fact that the water quality was adequately maintained in the culture tank during the experimental period. The survival rate was 100% in Trial 2. No obvious growth of fish was recorded during the experimental period of Trial 1, due to the low feeding rate.

Discussion

Performance of the system for the short-term culture and holding of fish

In Trial 1, the fish were fed approximately 0.5% of the total body weight of the fish during the 2-month culture period, and the water quality parameters were maintained well within the ranges commonly recommended for fish culture (Meade, 1985; Lewis and Moris, 1986; Hajek and Boyd, 1994.). In particular, the concentration of COD was well controlled by the foam fractionator and the Styrofoam bead filter. Although the exact quantity of organic matter (COD) oxidized in the Styrofoam bead filter is unknown, the organic matter removed should be linked principally with the trapping of solids in the Styrofoam bead filter, as indicated by the high concentration of solids in the backwash water. Catabolism of proteins results in the release of ammonia (Hopkins et al., 1993), which is toxic to fish; chronic toxicity is observed with concentrations as low as 1 mg/L (Menasveta et al., 2001). Concentrations of TAN and NO_2-N were maintained below 2 mg/L and mostly below 1 mg/L during the experimental period. However, the concentration of NO_3-N continued to build up. Regular replacement of the water, or a biological denitrification process where periodic replacement of the water is not practical, would be needed for long-term use of this type of aquarium system in the closed mode. The pH of the tank water declined as a result of nitrification and it became necessary to add sodium bicarbonate periodically, indicating the necessity of monitoring the pH in this system. In Trial 2, the fish were held for 24 hours without feeding and the water quality parameters in the culture tank were well controlled. Although the concentrations of TAN and NO_2-N increased quickly after stocking, they never reached harmful levels. These results indicate that this simple recirculating aquarium system can support a stocking density of at least 83 kg/m^3, based on the system water volume, or 107 kg/m^3, based on the culture tank water volume. However, the low TAN and NO_2-N concentrations in the culture tank water imply that the support capacity of this recirculating aquarium system is somewhat higher than those used in Trial 2.

The daily water exchange rate was around 5% of the whole system water volume in Trial 1, and this water loss was mainly due to the collection of foam condensate and backwashing. However, the accumulation of solids in the small water sump and the sudden high turbidity that was experienced during the experimental period indicated that rapid and thorough removal of solids from the system is not assured. Increasing the frequency of backwashing of the Styrofoam bead filter or increasing the foam overflow rate would be required to run this kind of system long-term. Alternatively, equipment with mechanical filtration could be considered. In Trial 2, without feeding, the water transparency was maintained to a high enough quality for exhibition purposes in restaurants.

Performance of the Styrofoam bead filter and the foam fractionator

Usually, the rate of TAN removal increased with increasing concentration of TAN at the inlet. In freshwater systems, TAN removal rates increase with increasing inlet TAN concentration, up to approximately 2 mg/L and plateau thereafter (Rittmann and Manem, 1992; Zhu and Chen, 1999). However, Nijhof and Bovendeur (1990) reported that a threshold inlet TAN concentration of more than 3 mg/L in a seawater system still allowed for maintenance of steady-state nitrification. In the present study, the inlet TAN concentration never exceeded 1 mg/L on the selected sampling days, indicating sub-optimal conditions for maximal TAN removal by the Styrofoam bead filter, and suggesting that the Styrofoam bead filter did not reach its highest nitrification capacity.

The volumetric TAN removal rate of 232.2 g/m^3·day obtained in the present study was lower than the volumetric TAN removal rate of 282 g/m^3·day obtained in our previous study (Peng et al., 2003), but comparable to that obtained (232 g/m^3·day) when the styrofoam bead filter was operated in a closed seawater recirculating system (Peng, 2003). These differences could be attributable to the different operating variables, especially the different compositions of organic matter and the organic matter loading rate. In experiments using glucose as organic matter, instead of organic matter originating from solids generated in an aquaculture system, the Styrofoam bead filter system ehibited a higher TAN removal rate (Peng et al., 2003). In aquaculture systems, nitrifiers may be inhibited, due to the accumulation of organic solids and heterotrophic biomass (Malone et al., 1993; Kamstra et al., 1998). In addition, nitrification is oxygen dependent; although DO concentrations in the outlet water from the Styrofoam bead filter never fell below 3.4 mg/L, there could be some oxygen-deficient areas within the interstitial spaces in the Styrofoam beads, due to uneven distribution of inlet water and/or the accumulation of solids.

Granular beads can provide capture of solids over a wide range of particle size. The filtration of suspended solids is accomplished by straining, interception, and settling within the granular bead matrix. Chen and Malone (1991) reported the removal, by a floating bead filter, of TSS equivalent to 10-25% of the weight of feed supplied. The TSS capture rate by the Styrofoam bead filter in the present study was 8.3-26.7% of the weight of feed supplied, similar to the values obtained by Chen et al. (1993c) and Delos Reyes et al. (1996). Thus, the Styrofoam bead filter not only helped to reduce TAN and NO_2-N concentrations in an aquaculture system, but also performed well for TSS capture.

The performance of foam fractionators for the removal of solids is highly dependent on the operating variables, including air flow rate, foam overflow height, and the composition of solids in the culture water. Usually, the volume of foam condensate increases and concentration of water contaminants in the foam condensate decreases with increasing air flow rates and decreasing foam overflow heights (Weeks et al., 1992; Peng and Jo, 2003b). In the present study, although the water flow rate and air flow rate through the foam fractionator column were relatively constant, the TSS concentrations in the foam condensates and the daily removal of TSS fluctuated considerably. These large fluctuations could be due to the variation in the concentration of TSS in the culture tank water during the experimental period.

Overall, this study demonstrated that, using a combination of Styrofoam bead filter for nitrification and solids trapping, and a foam fractionator for solids removal, TAN and COD levels can be reduced to levels suitable for short-term holding and culture of fish in a simple recirculating aquarium system. However, this system was not tested under different operating regimens, such as different feeding rates, stocking densities, etc. Therefore, further, more detailed and long-term studies should be conducted in order to improve our understanding, and to optimize the performance, of the whole system, as well as of the various individual treatment processes. Furthermore, since nitrate accumulation is expected to limit the ability to reuse water in marine applications (Whitson et al., 1993), especially in inland marine aquarium systems, the addition of a denitrification unit may be a necessity. Evaluation of a recirculating aquarium system, incorporating a denitrification process, would thus be a useful next step.

References

APHA. 1995. Standard Methods for the Examination of Water and Wastewater, 19th edition. American Public Health Association, Washington, D.C., USA.

Chen, S. and R.F. Malone. 1991. Suspended solids control in recirculating aquaculture systems. In: Engineering aspects of intensive aquaculture, proceedings from the aquaculture symposium. Cornell University, New York, pp. 170-186.

Chen, S., M.B. Timmons, Jr. J.J. Bisogni and D.J. Aneshansley. 1993a. Suspended solids removal by foam fractionation. Progressive Fish-culturist, 55, 69-75.

Chen, S., M.B. Timmons, D.J. Aneshansley and Jr. J.J. Bisogni. 1993b. Suspended solids characteristics from recircualting aquaculture systems and design implications. Aquaculture, 112, 143-155.

Chen, S., D.E. Coffin and R.F. Malone. 1993c. Production, characteristics, and modeling of aquaculture sludge from a recirculating aquaculture system using granular media filter. In: Techniques for modern aquaculture, Wang, J.K. ed. American Society of Agriculture Engineers, pp. 16-25.

Chen, S., D. Stechey and R.F. Malone. 1994. Suspended solids control in recirculating aquaculture systems. In: Aquaculture water reuse systems: engineering design and management, Timmons, M.B. and Losordo, T.M., ed. Elsevier, New York. pp. 61-100.

Delos Reyes, A.A. Jr. and T.B. Lawson. 1996. Combination of a bead filter and rotating biological contactor in a recirculating fish culture system. Aquacult. Eng., 15, 27-39.

Grasshof, K., K. Kremling and M. Ehrhardt. 1999. Methods of seawater analysis. 3rd edition. Wiley-VCH, Germany.

Hajek, B.F. and C.E. Boyd. 1994. Rating soil and water information for aquaculture. Aquacult. Eng., 13, 115-128.

Henderson, J.P. and N.R. Bromage. 1988. Optimizing the removal of suspended solids from aquacultural effluents on settlement lakes. Aquacult. Eng., 7, 167-181.

Hopkins, J.S., R.D. Hamilton, P.S. Sandifer, C.L. Browdy and A.D. Stokes. 1993. Effect of water exchange rate on production, water quality, effluent characteristics and nitrogen budgets of intensive shrimp ponds. J. World Aquacult. Soc., 24, 304-320.

Kamstra, K., J.W. van der Heul and M. Nijhof. 1998. Performance and optimization of trickling filters on eel farms. Aquacult. Eng., 17, 175-192.

Lewis, W.M. and D.P. Morris. 1986. Toxicity of nitrite to fish: A review. Trans. Am. Fish. Soc. 115(2), 183-195.

Lomax, K. M. 1976. Nitrification with water pretreatment on a closed cycle catfish culture system. Ph.D thesis, University of Maryland, College Park, MD.

Makinen, T., S. Lindgren and P. Eskelinen. 1988. Sieving as an effluent treatment method for aquaculture. Aquacult. Eng., 7, 367-377.

Malone, R.F., B.S. Chitta and D.G. Drennan. 1993. Optimizing nitrification in bead filters for warm-water recirculating aquaculture system. In: Techniques for modern aquaculture, Wang, J.K. ed. American Society of Agriculture Engineers, pp. 315-325.

Meade, J.W. 1985. Allowable ammonia for fish culture. Prog. Fish-Cult. 47(3), 135-145.

Menasveta, P., T. Panritdam, P. Sihanonth, S. Powtongsook, S. Cuuntapa and P. Lee. 2001. Design and function of a closed, recirculating seawater system with denitrification for the culture of black tiger shrimp broodstock. Aquacult. Eng., 25, 35-49.

Muir, J.F. 1982. Recirculated system in aquaculture. In: Recent advances in aquaculture, Volume 1, Muir, J.F. and Roberts, R.J. ed. Croom Helm and Westview Press, London.

Nijhof, M. and J. Bovendeur. 1990. Fixed film nitrification characteristics in sea-water recirculation fish culture system. Aquaculture, 87, 133-143.

Peng, L. 2003. Design, management and performance of a laboratory scale seawater recirculating system for Korean rockfish *Sebastes schlegeli* culture. Ph.D. Thesis, Pukyong National University, Busan, Korea.

Peng, L. and J.Y. Jo. 2003a. Nitrification efficiency in fixed film biofilters using different filter media in simulated seawater aquarium system. J. Aquacul., 16(4), 203-209.

Peng, L. and J. Y. Jo. 2003b. Removal of total suspended solids by a foam fractionator in a simulated seawater aquaculture system. J. Aquacul., 16(4), 216-222.

Peng, L., S.Y. Oh and J.Y. Jo. 2003. Organic matter and hydraulic loading effects on nitrification performance in fixed film biofilters with different filter media. Ocean and Polar Research, 25(3), 277-286.

Rittmann, B.E. and J.A. Manem. 1992. Development and experimental evaluation of a steady-state, multispecies biofilm model. Biotechnol. Bioeng., 39, 914-922.

Strickland, J.D.H. and T.R. Parson. 1972. A practical handbook of seawater analysis. J. Fish. Board. Canada.

Suh, K.H., B.J. Kim and S.K. Kim. 2000b. Characteristics of proteins and total suspended solids removal by counter current air driven type, high speed aeration type and venturi type foam separators in aquaculture water. J. Korean Fish. Soc., 33, 205-212.

Suh, K.H., B.J. Kim, Y.H. Kim, S.H. Lee, C.S. Suh, J.K. Cheon and J.Y. Jo. 2002. Performance of parallel current air driven type foam separator in a pilot-scale recirculating aquaculture system. J. Kor. Fish. Soc., 35, 140-145.

Timmons, M.B., S. Chen and N.C. Weeks. 1995. Mathematical model of a foam fractionator used in aquaculture. J. World Aquacult. Soc., 26, 225-233.

Weeks, N.C., M.B. Timmons and S. Chen. 1992. Feasibility of using foam fractionation for the removal of dissolved and suspended solids from fish culture water. Aquacult. Eng., 11, 251-265.

Whitson, J., P. Turk and P. Lee. 1993. Biological denitrification in a closed recirculating marine culture system. In: Techniques for modern aquaculture, Wang, J.K. ed. American Society of Agriculture Engineers, pp. 458-466.

Zhu, S.M. and S. Chen. 1999. An experimental study on nitrification biofilm performance using a series reactor system. Aquacult. Eng., 20, 245-249.

(Received March 2004, Accepted June 2004)