JOURNAL OF THE
WORLD AQUACULTURE SOCIETY

Vol. 42, No. 2
April, 2011

Evaluation of a Low-head Recirculating Aquaculture System Used for Rearing Florida Pompano to Market Size

TIMOTHY J. PFEIFFER[1] AND MARTY A. RICHE

USDA Agricultural Research Service, Sustainable Marine Aquaculture Systems, 5600 US 1 North, Ft. Pierce, Florida 34946, USA

Abstract

A low-head recirculating aquaculture system (RAS) for the production of Florida pompano, *Trachinotus carolinus*, from juvenile to market size was evaluated. The 32.4-m^3 RAS consisted of three dual-drain, 3-m diameter culture tanks of 7.8-m^3 volume each, two 0.71-m^3 moving bed bioreactors filled with media (67% fill with K1 Kaldness media) for biofiltration, two degassing towers for CO_2 removal and aeration, a drum filter with a 40-μm screen for solids removal, and a 1-hp low-head propeller pump for water circulation. Supplemental oxygenation was provided in each tank by ultrafine ceramic diffusers and system salinity was maintained at 7.0 g/L. Juvenile pompano (0.043 kg mean weight) were stocked into each of the three tanks at an initial density of 1.7 kg/m^3 (300 fish/tank). After 306 d of culture, the mean weight of the fish harvested from each tank ranged from 0.589 to 0.655 kg with survival ranging from 57.7 to 81.7%. During the culture period, the average water use per kilogram of fish was 3.26 or 1.82 m^3 per fish harvested. Energy consumption per kilogram of fish was 47.2 or 22.4 kwh per fish harvested. The mean volumetric total ammonia nitrogen (TAN) removal rate of the bioreactors was 127.6 ± 58.3 g TAN removed/m^3 media-d with an average of 33.0% removal per pass. Results of this evaluation suggest that system modifications are warranted to enhance production to commercial levels (>60 kg/m^3).

Land-based recirculating aquaculture systems (RASs) using circular dual-drain culture tanks have been able to increase fish production while conserving water, improving overall waste capture efficiency, and maintaining excellent water quality for a variety of freshwater and marine fish species (Timmons et al. 1988). The hydraulics for water circulation in RAS is basically of two types – pressurized, high-head systems and low-head systems. In pressurized systems, centrifugal pumps are often utilized to transfer water from one location to another of a higher elevation or to increase system pressure (head) for filtration, aeration, degassing, and distribution of water to the culture tanks. An advantage of such a system is the hydraulic link between source, and point of discharge is relatively independent of the pipe's geometry but a change in flow at one distribution point will influence flow at another point. Centrifugal pumps can be efficient mechanisms for moving water, provided the correct pump is selected for the job. However, commercial aquaculture production is driven by production costs and economic returns. In tank-based RAS, one of the main production costs in addition to feed is electrical energy for pumping water (Dunning et al. 1998; Colt et al. 2008). In low-head systems, large volumes of water can be moved using significantly lower electrical energy, thereby improving the economic returns of production. Typically, low-head systems include airlift pumps, axial-flow propeller pumps, or some combination of the two for water movement through the system. In either situation, with low-head pumps, there is limited availability of head (usually <4 m) resulting in additional system design and engineering considerations. The layout and sizing of the piping systems are critical so that solids or effluent wastes do not collect in the pipes, venting is also important so that air locks do not develop, and treatment components need to operate with minimal pressure so that system

[1] Corresponding author.

Published 2011. This article is a US Government work and is in the public domain in the USA.

flow is not significantly reduced. Additionally, piping construction materials should be properly sized to reduce friction losses, slope of piping should be sufficient to ensure suitable pipe drainage, there should be minimal fittings that increase head losses, and the height elevation between pump source and tank discharge needs to be within the head limits of the pump capacity for adequate tank and system treatment water flow. Properly designed and constructed low-head RAS with consideration to form and function can provide a safe, flexible, and low-energy alternative to high-head pump systems.

The objective of this study was to design and evaluate a low-head RAS for the production of Florida pompano, *Trachinotus carolinus*. The Florida pompano was selected because it is a promising species for marine aquaculture due to its good growth rate, high survival, ease of handling, and ready acceptance of formulated feed (Lazo et al. 1998). The Florida pompano is also common along the Florida coasts (Gilbert and Parsons 1986; Watanabe 1995), and depending on time of year and availability, pompano seafood products command a superior market value (National Marine Fisheries Service 2007).

Materials and Methods

System Description

The 32.4-m^3 low-head RAS is located in the United States Department of Agriculture (USDA) Agricultural Research Service's Sustainable Tank Aquaculture Recirculating Research Facility within the aquaculture development park of Harbor Branch Oceanographic Institute – Florida Atlantic University, Fort Pierce, Florida. The low-head RAS contained three 8-m^3 (i.e., 3.05-m diameter and 1.2-m deep) circular "Cornell-type" dual-drain fiberglass culture tanks (Fig. 1). Water from the sidewall of each tank exits into a 15.2-cm-diameter polyvinylchloride (PVC) Schedule 40 drain line piped to a microscreen drum filter equipped with a 40-µm screen to remove suspended solids (Hydrotech Model 801, Water Management Technologies, Inc., Baton Rouge, LA, USA). Backwash discharged from the microscreen drum filter was piped to the facility central drain that flows to an outside sump for holding and pumping to the park's settling ponds. Microscreen drum filtrate flowed into a circular sump (8-m^3, 3.05-m diameter, and 1.2-m deep), where it combined with makeup saltwater and freshwater well water. The makeup freshwater into the sump was controlled by a mechanical float valve. The makeup saltwater into the sump was controlled by the YSI 5200 recirculating system monitor (YSI Inc., Yellow Springs, OH, USA). The multiprobe of the YSI 5200 measured salinity, and based on the salinity reading, an actuator ball valve was opened or closed to maintain the salinity of the system water circulating in the sump between a range of control values (i.e., ±0.5 psu). When the sump water level was low and the mechanical

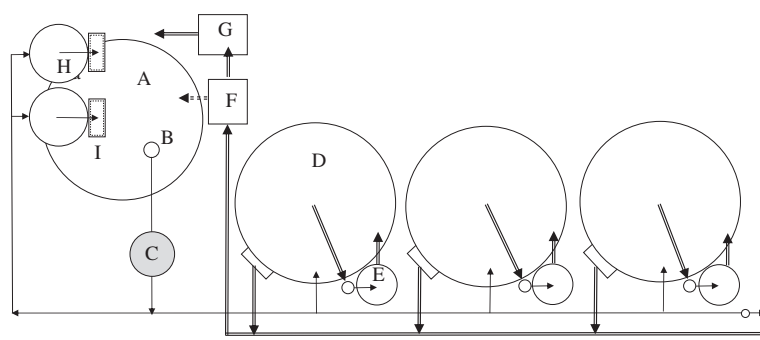

FIGURE 1. *Process flow drawing of the low-head recirculating aquaculture systems used for the production of low-salinity finfish species at the USDA ARS Sustainable Marine Aquaculture Systems facility in Fort Pierce, Florida. Key components are (A) pump sump, (B) propeller pump, (C) oxygen injection cone, (D) dual drain Cornell tank, (E) wave vortex chamber, (F) diverter box, (G) rotary screen drum filter, (H) moving bed bioreactor, and (I) degassing towers.*

float valve in the open position, makeup saltwater entered the sump if the salinity was below the control range and the actuator ball valve was in the open position. Both water sources are subjected to biological and mechanical filtration before storage and use in the facility.

A low-head, continuous duty propeller pump (1 hp, 3 Ph, 208 VA; Tsurimi, Model PAB5, Aquatic Eco-Systems, Apopka, FL, USA) was used to pump water from the sump to a side loop biofiltration/degassing setup and to return water to the tanks through a 2.2-m^3 oxygen injection cone (Waterline Ltd., Charlottetown, Prince Edward Island, Canada). The side loop biofiltration/degassing treatment unit consisted of two 0.71-m^3 Clearwater™ Low-Space Bioreactors (Aquatic EcoSystems, Apopka, FL, USA) filled with 67% type K1 Kaldness media for biofiltration. Air flow to the reactors for continuous movement of the media was provided by a regenerative blower (2.5 hp, 1 Ph, 208 VA; Sweetwater, Model S51, Aquatic Eco-Systems) at manufacturer's recommended airflow rate of 0.13 m^3/min. Outflow from each bioreactor flowed into a six chamber degassing tower (1.65 m in height × 0.5-m wide × 0.5-m deep) before re-entering the pump sump. Each chamber of the tower held a tray in which a perforated plate (9.5-mm diameter holes) was placed for water distribution. The degassing tower was passively ventilated and no air was forced through the tower.

Return flow to the tanks after the oxygen injection cone was through a 10.2-cm-diameter PVC Schedule 40 pipe. A 5.1-cm diameter PVC pipe with ball valve was plumbed off the main return line at each tank to serve as the tank inlet. The inlet line extended to approximately 60% of the tank depth. After the tanks, the line was plumbed into the system drain line, which was plumbed to the microscreen drum filter. A ball valve was placed in line prior to this connection to control flow to the tanks and helped purged the drain line of any settled or collected material.

The bottom drain of each tank sump was connected to a 600-L wave vortex chamber (Model no. WLF36, Aquatic Eco-Systems). Water gravity flowed from the tank sump into the vortex chamber and was airlifted back into the tanks. The airlifted flow rate through the vortex chambers was approximately 150 L/min at an air flow rate of approximately 60 L/min and a pressure of 1.3 m of water. The settled solids collected in the wave vortex chambers were purged out of the units twice daily and the chambers were drained and rinsed every 3 d.

Polypropylene nets (1.9-cm knotless mesh) were placed over each tank to prevent fish escape. A 12 light : 12 dark photoperiod was provided with overhead fluorescent lights. The system is enclosed under half of two Quonset style greenhouses that are gutter connected and measures 46.3 m in length and 22.9 m in width. The greenhouse double layer polyethylene plastic covering was replaced with 26 gauge, white galvanized steel panels and the interior walls insulated with 1.9-cm thick R-max material. Aluminum intake shutters and exhaust fans on either length of the green house provide ventilation and circulation of air through the greenhouse structure. A power exhausted gas fired unit heater is located at the rear of each greenhouse to provide supplemental heating during the cooler winter temperatures.

Fish, Feed, and Feeding

In May of 2006, each tank of the low-head system was stocked with 300 Florida pompano, which were reared from eggs produced onsite. The weight of the fish stocked to initiate the 306-d study was 0.043 kg/fish. Fish were hand fed during work hours (0800–1700) two to five times a day depending on how much feed was being provided per day so that little or no waste feed was observed. The targeted daily feed rate at the start of the study was 3% of the estimated fish biomass in the tank. Mortalities were removed and recorded daily and used in adjusting the daily feed rate. Fish were fed an extruded floating pellet (46% protein and 16% fat), which ranged in size from 3.5 to 7.5 mm (Silver Cup Fish Feed, Nelson & Sons, Inc., Murray, UT, USA). During the 306-d trial, fish growth was regularly assessed to adjust the daily feed rates and determine the specific growth rate (SGR).

Approximately 10% of the fish population of each tank was randomly collected to determine the average fish weight in the tank. Eight sampling events were conducted and the time between each event was from 2 to 6 wk. The SGR was calculated using the formula: SGR = $\ln (W_t / W_i)/t$, where W_t is the weight at the end of a sampling period, W_i the initial weight at the beginning of the sample period, and t the time of the sampling period in days. The food conversion rate (FCR) was calculated using the formula: FCR = g dry weight feed fed/g wet weight gain.

At termination of the rearing trial, the entire population of fish from each tank was harvested, counted, and weighed. A subsample of 30 fish from each tank was used to determine fillet dress-out percentage and mean harvest weight.

Water Sampling Events

Water quality measurements were obtained at the system diverter box, which collects the effluent flow from the side box of each tank and is prior to the drum filter (Fig. 1). Water quality parameters including temperature, salinity, pH, dissolved oxygen, total ammonia nitrogen (TAN), and nitrite-nitrogen (NO_2-N) of the system were measured daily at approximately 0900 h during the experimental period. Alkalinity of the low-head RAS was measured twice weekly and system alkalinity was adjusted to maintain at 200 mg/L as $CaCO_3$. Temperature, salinity, pH, and dissolved oxygen were measured using an YSI 556 multiprobe handheld meter (YSI Inc.). TAN and NO_2-N were determined via colorimetric assays (methods 8155 and 8153, respectively) using a HACH D/R 2500 spectrophotometer (HACH Co., Loveland, CO, USA). Alkalinity was determined using HACH digital titration method 8203. Sodium bicarbonate was added daily to systems to maintain alkalinity and pH. Values reported represent mean ± SD.

System Water Use and Filter Nitrification Rates

Water use was measured daily from positive displacement water meters installed on the incoming 2.5 cm-diameter freshwater and saltwater lines leading to the float valves on the system sump. A water meter was also installed on the 2.5-cm-diameter rinse water line of the microscreen drum filter. Recording of the water meter values were conducted daily as part of the system morning water quality sampling regime. The percentage water usage for each line was determined by dividing the volume used during 24 h by the system volume, 32.4 m^3. The volume of water used accounted for all water purged from the vortex filters, system sump, tank sumps, and line purging. Water inflow to the system sump to provide the makeup saltwater and freshwater was controlled by ball valves on the incoming lines that were set and adjusted to provide the appropriate system salinity. The ball valves were positioned after the water meters.

To obtain the apparent volumetric nitrification rate (VTR) of the Low-Space Bioreactor (LSB) moving bead biofilters, discrete inlet and outlet water samples from each of the reactors were collected for TAN analysis. Samples were collected twice weekly throughout the trial period to obtain a range of VTR data with increasing levels of influent TAN concentration and system feed loading rates. Water samples for TAN analysis were analyzed immediately after collection using HACH D/R 2500 portable spectrophotometer, Method 8038. Flow rates into the filters were measured with an Ultrasonic Flow meter (PortaFlow SE model, Greyline Instruments, Messena, NY, USA). The VTR was calculated by the following equation:

$$\mathrm{VTR} = K_C\ (\mathrm{TAN_{IN}} - \mathrm{TAN_{OUT}})\, Q_R / V_b$$

where VTR is the g TAN converted per m^3 of filter media per day, Q_R is the water flow rate through the filter (Lpm), K_C is the unit conversion factor of 1.44, $\mathrm{TAN_{IN}}$ and $\mathrm{TAN_{OUT}}$ are the influent and effluent total ammonia concentrations in mg/L, and V_b is the volume of the filter media, 0.71 m^3 for the LSBs.

The percentage removal of TAN on a single pass through the filter was obtained by the following equation: % removal = $(\mathrm{TAN_{IN}} - \mathrm{TAN_{OUT}})/\mathrm{TAN_{IN}} \times 100$. The percentage removal

rates were obtained for various influent TAN concentrations and flow rates through the filters.

Results and Discussion

System Water Quality

The metrics describing the water quality of the low-head RAS used for the culture of Florida pompano are presented in Table 1. The dissolved oxygen of the water exiting the culture tanks, measured at the system diverter box, was 8.2 ± 1.0 mg/L. The dissolved oxygen exiting the tanks was slightly greater than saturation based on the system's average temperature and salinity. Initially, the oxygen injection cone was utilized for oxygen supplementation but the high oxygen input pressure and volume (20 psi, 5 Lpm) created a buildup of O_2 gas in the cone's upper chamber, which reduced the amount of system flow. The O_2 input pressure and volume was subsequently reduced (5–7 psi, 2–3 Lpm), which did not alleviate the problem but only increased the time it took for the back pressure to build and reduce amount of supplemental O_2 delivered to the tanks. By constantly purging the excess pressure from the cone, the build up could be minimized, but the problem was not resolved. As a result, flow through the cone was bypassed, which increased the overall flow to the tanks because of the decrease in head loss. Oxygen supplementation to the tanks was accomplished by placing ceramic ultrafine bubble diffusers (Model No. AS303, Point Four Systems Inc., Coquilam, BC, Canada) directly into each tank and running them continuously to maintain saturation conditions.

TABLE 1. *Metrics that describes the water quality of the low-head system used for the culture of Florida pompano.*

Parameter	Average + SD	Range
Dissolved oxygen (mg/L)	8.2 ± 1.0	6.2–10.9
Temperature (C)	26.2 ± 1.0	22.9–28.7
Salinity (ppt)	7.0 ± 0.7	6.0–15.0
pH	7.8 ± 0.3	6.9–8.7
Alkalinity (mg/L as $CaCO_3$)	216 ± 44	137–339
Total ammonia nitrogen, TAN (mg/L)	0.46 ± 0.27	0.07–1.25
Nitrite nitrogen, NO_2-N (mg/L)	0.241 ± 0.205	0.000–1.125
Total suspended solids (mg/L)	6.52 ± 3.23	1.00–11.60

Water temperature ranged from 22.9 to 28.7 C with a mean temperature of 26.2 C ± 1.0 C. The system did not have a supplementary heating source for the culture water and the water temperature was a reflection of the ambient air temperature in the facility. Salinity was maintained at 7.0 ± 0.74 and ranged from 6 to 15 g/L during the study. The maximum salinity measured (15 g/L) was the result of a float valve malfunction allowing excess saltwater to be added to the system before proper operation was restored. System pH and alkalinity averaged 7.8 ± 0.3 and 216 ± 44 mg/L as $CaCO_3$, respectively. Alkalinity and pH were maintained by the daily addition of sodium bicarbonate ranging from 0.5 kg/d at the beginning of the study to a peak daily addition of 2.0 kg/d at the end of the study. The levels of TAN and NO_2-N were both below 1.25 mg/L and averaged 0.46 ± 0.21 and 0.241 ± 0.205 mg/L, respectively. The highest TAN and NO_2-N levels were measured during the peak system feed load rate of 0.22 kg feed/m^3/d of system volume (32.4 m^3). The total suspended solid concentration (TSS) in the system was 6.62 ± 3.23 mg/L and ranged from 1.0 to 11.6 mg/L. Initially, a 60-μm screen was used on the drum filter, but as the feed load increased, the TSS in the system culture water began averaging 10 mg/L, an increase from the weekly average of roughly 4.0 mg/L. Thus, the screen was changed to a 40-μm screen on Day 154 and the TSS of the system culture water decreased to the range of 4–5 mg/L.

Fish Growth and Feed Conversion

Metrics for Florida pompano growth in each of the culture tanks during the system performance study is presented in Table 2. The average weight (±SD) of harvested fish in each tank from a sample number of 30 fish was 0.636 ± 0.142, 0.655 ± 0.135, and 0.589 ± 0.122 kg for Tanks 1, 2, and 3, respectively. The weight range of these samples was 0.362–0.980 kg for Tank 1, 0.324–0.934 kg for Tank 2, and

TABLE 2. *Metrics for the Florida pompano cultured in the low-head system tanks during the system performance study.*

Tank no.	Percentage survival	Harvested fish weight (kg, average ± SD)	Specific growth rate (per day)	Food conversion ratio	Mean % body weight feed per day (average ± SD)	Maximum daily feed rate (% BW/d)	Harvested biomass density (kg/m^3)	Percent fillet (average ± SD)
1	65.7	0.636 ± 0.142	0.0088	4.2	2.35 ± 0.76	3.8	16.8	41.5 ± 3.8
2	57.7	0.655 ± 0.135	0.0081	4.2	2.23 ± 0.73	3.5	17.1	43.9 ± 3.6
3	81.7	0.589 ± 0.122	0.0087	3.4	2.12 ± 0.58	3.4	19.9	50.3 ± 13.1

0.388–0.968 kg for Tank 3, respectively. The tanks were stocked with a total of 300 pompano each and survival in each tank ranged from 57.7 to 81.7% and the SGR for the harvested fish from each tank ranged from 0.0081 to 0.0088/d. The SGR decreased with time, dropping from a peak SGR of 0.0187/d when the pompano average 0.206 kg to less than 0.0036/d once the pompano were near 0.400 kg in weight. Similar decreases in growth for pompano have been reported by McMaster (1988) and Weirich et al. (2006, 2009). The average daily feed rate, based on percentage body weight of the fish, ranged from 2.12 to 2.35% body weight per day and the maximum daily feed rate ranged from 3.4% in Tank 3 to 3.8% body weight per day in Tank 1. The feed conversion rate of 3.4 was lowest in Tank 3, which had the greatest survival, lowest average daily fed rate, and highest culture density. Tanks 1 and 2 had an FCR value of 4.2, both of which also had lower culture densities. Weirich et al. (2009), in their study with Florida pompano in a high head RAS at 5 mg/L salinity determined food conversion efficiency to be lower in the tanks with a lower density (14.2 kg/m^3) compared with the higher density tanks (25.5 kg/m^3). Dress out percentage for fillets was 41.5% in Tank 1, 43.9% in Tank 2, and 50.3% in Tank 3. During the production period, no disease outbreaks occurred and no chemotherapeutics or antibiotics were used.

Unit Process Treatment Efficiency and System Metrics

Several of the metrics to characterize system performance as well as the intensity of energy and water use are reported in Tables 3 and 4. Tank turnover time was approximately 0.7 h, equating to roughly 1.5 tank turnovers per hour. The objective of two turnovers per hour could not be obtained because of the hydraulics and height of the bioreactors above the sump. Water from the sump was pumped to a height of 3 m to enter the bioreactors located above the sump. This height limited the amount of water that could be directed to the tanks and still satisfied the flow requirements of the bioreactors. Reducing the height of the reactors or modifying the sump/biofilter design would allow greater flow to the tanks. The system turnover rate through the drum filters was one system volume (32.4 m^3) in approximately 1 h and one system volume through the bioreactors (for nitrification processes) every 80 min or 1.3 h.

TABLE 3. *Metrics that describe the efficiency of production of the low-head RAS used for culture of the Florida pompano in a low-salinity environment.*

Parameter	Value ± SD
Mean hydraulic retention time (culture tank)	0.69 h
System turnover	
Drum filter	0.96 h
Biofilter	1.29 h
System water exchange rate (% total volume/d)	11.3 ± 13.6
Freshwater makeup volume (% system volume/d)	6.1 ± 11.6
Saltwater makeup volume (% system volume/d)	1.7 ± 3.7
Drum filter rinse water volume (% system volume/d)	3.7 ± 2.7
Maximum fish density in culture tank (kg/m^3)	19.9
Maximum system feed load rate (kg/m^3)	0.22
Mean cumulative feed burden (g feed/L makeup water)	8.0 ± 13.1

The daily water usage of the system as a percentage of system volume was approximately

TABLE 4. *Energy requirements and approximate costs of operation for each component of the low-head RAS under 24 h of daily operation (assuming electricity costs are $0.10/kwh).*

Unit	HP	kwh	kwh/d	$/d
Propeller pump, 3 ph	1.0	1.20	28.8	2.88
Regenerative blower, 1 ph	2.5	0.62[a]	14.9[a]	1.25
Microscreen drum filter with high-pressure booster pump	0.25	0.06[b]	1.5[b]	0.15
Total			45.2	4.52
Energy used per kilogram produced (kwh/kg fish produced)			40.3	
Energy used per unit fish harvested (kwh/fish)			22.4	
Energy cost per kilogram produced ($/kg fish produced)			4.03	
Energy cost per unit fish harvested ($/fish)			2.24	

[a]The systems utilized one fifth of the air provided by the 2.5 hp regenerative blower. Thus, the kwh and kwh/d presented are only one fifth of the actual daily energy used by the blower.

[b]The kwh usage is for the rotating microscreen drum filter with a 40-μm screen and a maximum fish culture density of 20 kg/m^3. Different screen mesh size and fish/feed loading rate would affect the operation of the drum filter. A greater fish density and feed load rate would likely increase the drum motor operation of the filter and increase the kwh/d. A larger screen mesh size would reduce frequency of filter backwashes thus reducing the motor operation of the pump and drum motor for rotation and overall kwh. The HP values are nominal values and the kwh values are measured values.

11.3% or roughly 3.7 m^3/d. Makeup freshwater for the system was the bulk of the water use, 6.1% of system volume or 1.97 m^3/d, followed by rinse water for the drum filter, 3.7% of system volume or 1.20 m^3/d, and saltwater was approximately 1.8% of system volume or 0.58 m^3/d. From a water use perspective, the water usage per production was 1.82 m^3 per harvested fish or 3.26 m^3 of water/kg fish.

The cumulative feed burden (CFB) is calculated by amount of feed loaded into the system divided by the volume of makeup water and is a way to classify system intensity (Colt et al. 2006). An intensive RAS would have a higher value than a flow-through system because less water is used per amount of feed provided. Typically, flow-through or partial flow-through systems utilized in salmon culture have values less than 100 mg of feed per liter of makeup water volume (Summerfelt et al. 2004, 2009). The CFB for this system averaged 8.0 ± 13.1 g feed per liter makeup water volume, indicating a much greater intensive system than flow-through systems because less makeup water was used per kilogram of feed provided. CFB has not been previously published for marine RASs. Currently, other marine low-head recirculating production systems at the facility with greater fish density but of similar system volume (40 m^3) have a CFB value that ranges between 3 and 5. These systems are operating with a fish biomass 3–4 times greater than this study (60–90 kg/m^3) and a daily feed rate that is 2.5 times higher (25–30 kg/d). The more feed loaded into the system because of a greater biomass of fish in the tanks with a lower volume of makeup water will result in a higher CFB value. The CFB value thus serves as a valuable parameter for evaluating future system modifications to enhance system performance and intensity.

Table 4 provides the direct energy costs as measured by a Power Logger (Fluke 1735, Everett, WA, USA) of the system components and does not account for facility energy use (lights, outlets, and fans) or water pretreatment energy use. The major energy component was the axial flow propeller pump, which used 1.2 or 28.8 kwh/d. The energy calculation from the 2.5-hp regenerative blower was divided by five because the system's air needs were approximately one fifth of the blower's capacity. Air from the blower was used to lift water back into the tanks from the vortex chambers and for media movement in the bioreactors. The water flows from the tank center drain, which is airlifted into the vortex chambers and gravity flowed back into the tanks, ranged from 95 to 115 L/min. This flow required approximately 5.1–5.8 m^3/h of air at less than 1.25 m of head (<2 psi). The air flow to the low-space bioreactors for media movement was 7.7 m^3/h.

The blower delivered a volume of air equal to 125 m^3/h at a head pressure of 1.25 m, and the energy cost for that amount of air is 3.1 kwh. As the system utilized approximately one fifth of the air produced by the blower (5.5 m^3/h × 3 for airlift flow through the vortex chambers + 7.7 m^3/h for media movement in the reactors = 24.2 m^3/h), one fifth of the energy of the blower was applied to the system energy budget to supply the air needs. Total system energy used was 45.2 kwh/d, which is about half of the energy costs of the high head system described by Weirich et al. (2009) in their pompano production study. The energy produced per kilogram of pompano used was 40.3 kwh, and energy used per unit fish harvested was 22.4 kwh. The energy costs per kilogram of pompano produced in the low-head RAS was $4.03 and the energy cost per fish harvested was $2.24. These calculations were based on electrical costs of $0.10/kwh. These numbers obviously do not reflect production as efficient as those achieved in commercial operations, where scale of size can result in greater efficiency, both in terms of water and energy efficiency.

Figures 2 and 3 provide a graphic illustration of the moving-bed biofilm reactor ammonia removal efficiency. Fig. 2 illustrates the volumetric TAN removal rate of the two reactors increased with an increasing influent TAN concentration. This observation was anticipated as numerous studies have indicated that increasing the TAN concentration in biofilters results in proportional improvement in the filter's conversion ability (Rusten et al. 1995, 2006; DeLos Reyes and Lawson 1996; Malone et al. 1999; Drennan et al. 2006; Pfeiffer and Malone 2006). The average volumetric TAN removal rate was 127.6 ± 58.3 g TAN/m^3 media-d with a range of 23.5–254.1 g TAN/m^3 media-d. Each reactor had approximately 67% fill of Kaldness type K1 plastic biofilm media. The flow through the two bioreactors averaged 220.2 ± 64.9 L/min, giving a hydraulic retention time (HRT) in the moving bead bioreactors of approximately 5 min. The average TAN removal per pass was 33.0 ± 11.9% with a range of 8.3–62.4%. Fig. 3 illustrates the increase in removal efficiency with lower flow resulting in a greater HRT. Manufacturer's recommended flow rate is in the range of 95–340 L/min with suggested air flow of 7.6 m^3/h. The bioreactors were operated in the recommended flow range with the suggested amount of aeration for proper media movement. Nitrification rates in seawater are typically lower than that in freshwater (Bovendeur 1989), and nitrification rates of a

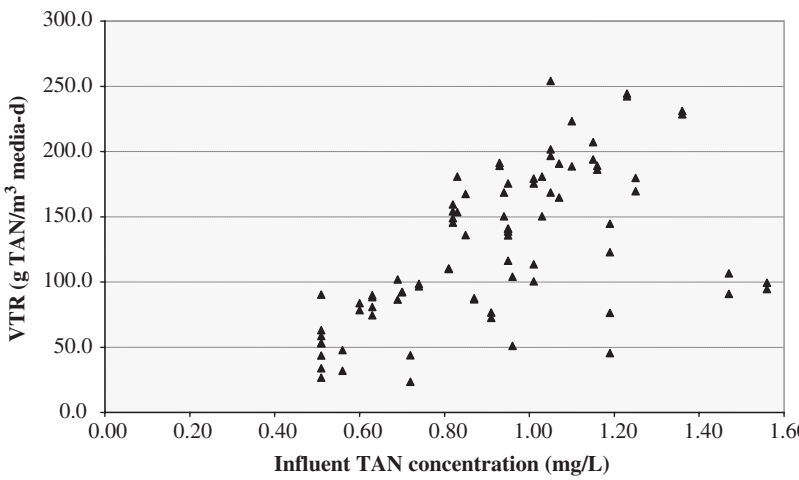

FIGURE 2. *Volumetric nitrification rates (VTRs) of a 0.71-m^3 moving bed bioreactor with 67% fill of type K1 Kaldness media for a range of influent TAN concentrations in a low-head recirculating aquaculture system used in the culture of Florida pompano and with salinity of 7.0 g/L.*

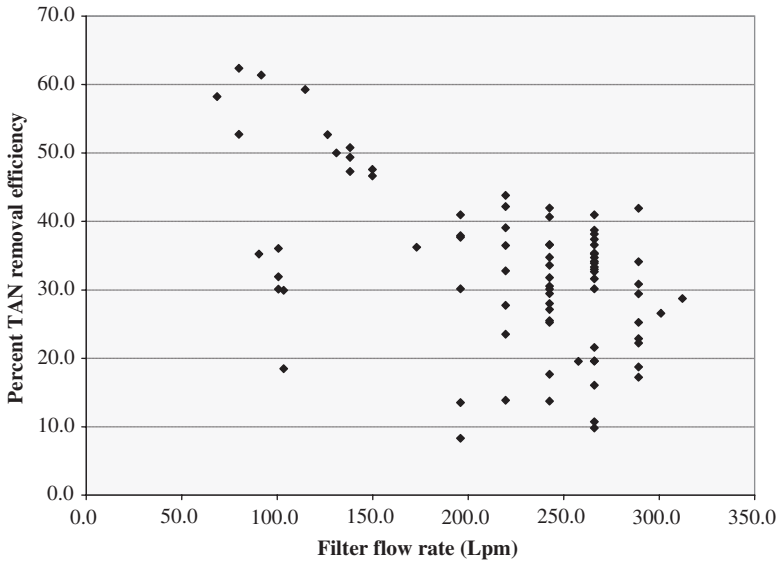

FIGURE 3. *Percentage TAN removal efficiency of a 0.71-m^3 moving bed bioreactor with 67% fill of type K1 Kaldness media in a low-head recirculating aquaculture system used for the culture of Florida pompano at a salinity of 7.0 g/L.*

moving bed bioreactor for a turbot farm in Portugal (21 g/L salinity, temperature 17.5 C) indicated 60% nitrification rate of what could be expected in a freshwater system (Rusten et al. 1995). The specific biofilm surface area of the K1 Kaldness media is 500 m^2/m^3 (Rusten et al. 2006), resulting in an average aerial nitrification rate of 0.26 ± 0.12 g TAN/m^2 media-d with a range of 0.05–0.51 g TAN/m^2 media-d. The aerial nitrification rates reported for rotating biological contactors in a hybrid striped bass RAS facility were 1.2 g/m^2 media-d (Van Gorder and Jug-Dujakovic 2004). Comparative aerial nitrification performance by submerged biofilters, bead filters, and fluidized sand filters are 0.30–0.60 g/m^2-d (Wheaton et al. 1994), 0.20–0.25 g/m^2-d (Wheaton et al. 1994), and 0.25–0.35 g/m^2-d (Thomasson 1991), respectively. Summerfelt (2006) reported a VTR of the CycloBio® fluidized sand filter in a recirculating salmonid system (The Conservation Fund Freshwater Institute, Shepherdstown, WV, USA) in the range of 140–170 g/m^3-d of expanded bed depth. The nitrification ability of moving-bed biofilm reactor used in this study has opportunity for improvement and effects of reactor and aeration grid design, biofilm carriers, and reactor media volume need to be investigated to improve the biofilter nitrification capabilities.

Routine System Maintenance

Routine maintenance of the low-head RAS was minimal. The drum filter screens were pressure washed biweekly and the spray nozzles cleaned on an as needed basis. Drain and return lines were cleaned out biweekly to reduce the accumulation of biofilm growth in the pipes. The tank side boxes were cleaned twice weekly and the tank walls were scrubbed monthly. The vortex chambers were purged twice daily with an average purge volume of approximately 26.0 ± 5.8 L. Once every 3 d, a vortex chamber was completely drained with the average drain volume of 575.2 ± 25.5 L and biofilm growth on the walls was washed down. The solids in the vortex chamber purge was measured on three occasions and found to be 115.8 g ± 33.0 g dry weight ($n = 6$) when the daily tank feed rate was approximately 2.1 kg/d. At a lower daily feed rate, 0.77 kg/d, the amount of solid in the vortex chamber purge was 49.3 g ± 23.5 g dry weight ($n = 3$). The amount of solid from the vortex chamber drain volume

at these two feed rates was 705.5 ± 83.9 g and 338.7 ± 16.5 g dry weight, respectively. The sump was drained biweekly for removal of accumulated solids on the bottom, and the sides were scrubbed monthly to minimize biofilm growth on the walls. The trays in the degas towers were rinsed monthly to remove biofilm growth on the perforated plates and tray sides.

Summary

The objective of development of a low-head RAS for the production of Florida pompano has been successful. To improve production of the low-head RAS to commercial levels (>60 kg/m^3), system modifications are warranted. To accomplish the objective that the design changes recommended include installation of a fine solid-removal device, improved method of supplemental oxygenation and control, and a larger biofiltration unit with improved or enhanced nitrification abilities. These data represent practical performance data for low-head RASs that aquaculturists can utilize for low-salinity RAS designs. The data presented are a supplement to practices and performances of system components already established and should be used with the best management practices to optimally maintain a RAS for food fish production.

Acknowledgments

This work is a technology transfer application from research and development supported by the USDA Agricultural Research Service under the National Aquaculture Program under Project number 6225-63000-007-D, titled Engineering and Production Strategies for Sustainable Marine Aquaculture. Use of trade names or mention of specific companies does not imply endorsement of these companies or their products by the Agricultural Research Service of the USDA and is mentioned solely for the purpose of providing specific information. Appreciation and recognition is extended to USDA ARS technicians Todd Lenger and Dave Haley and Harbor Branch personnel James Webb and David Wood for their technical assistance. We thank Jerry Ludwig, Paul Wills, Ken Riley, and Robert Rode for critical review of this article.

Literature Cited

Bovendeur, J. 1989. Fixed-biofilm reactors applied to wastewater treatment and aquacultural water circulation systems. PhD thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Colt, J., S. Summerfelt, T. Pfeiffer, S. Fivelstad, and M. Rust. 2008. Energy and resource consumption of land-based Atlantic salmon smolt hatcheries in the Pacific Northwest (USA). Aquaculture 280:94–108.

Colt, J. S., J. Lamoureux, R. Patterson, and G. Rogers. 2006. Reporting standards for biofilter performance studies. Aquacultural Engineering 34:377–388.

DeLos Reyes, A., Jr. and T. B. Lawson. 1996. Combination of a bead filter and RBC fish culture system. Aquacultural Engineering 15(1):27–39.

Drennan, D. G., II, K. C. Hosler, M. Francis, D. Weaver, E. Aneshansley, G. Beckman, C. H. Johnson, and C. M. Cristina. 2006. Standardized evaluation and rating of biofilters, II. Manufacturer's and user's perspective. Aquacultural Engineering 34:403–416.

Dunning, R. D., T. M. Losordo, and A. O. Hobbs. 1998. The economics of recirculating tank systems: a spreadsheet for the individual analysis. SRAC Publication No. 456. Southern Regional Aquaculture Center, Stoneville, MS, USA.

Gilbert, C. and J. Parsons. 1986. Species profile: life histories and environmental requirements of coastal fishes and invertebrates (South Florida): Florida pompano. U.S. Fish and Wildlife Service Biological Report 82 (11.42), U.S. Department of the Interior, Washington, DC.

Lazo, J. P., D. A. Davis, and C. R. Arnold. 1998. The effects of dietary protein level on growth, feed efficiency and survival of juvenile Florida pompano (*Trachinotus carolinus*). Aquaculture 169:225–232.

Malone, R. F., L. E. Beecher, and A. DeLos Reyes, Jr. 1999. Optimizing nitrification bead filters for warm water recirculating aquaculture. Pages 315–325 *in* J. K. Wang, editor. Techniques for modern aquaculture. American Society of Agricultural Engineers, St. Joseph, MI, USA.

McMaster, M. 1988. Pompano aquaculture: past success and present opportunities. Aquaculture Magazine (May/June):28–34.

NMFS (National Marine Fisheries Service). 2007. Fisheries of the United States 2006. National Marine Fisheries Service, Office of Science and Technology, Fisheries Statistics and Economics Division, Silver Springs, MD, USA.

Pfeiffer, T. J. and R. F. Malone. 2006. Nitrification performance of a propeller-washed bead clarifier supporting a fluidized sand biofilter in a recirculating warmwater fish system. Aquacultural Engineering 31(1):80–92.

Rusten, B., B. Eikebrokk, Y. Ulgenes, and E. Lygren. 2006. Design and operation of the Kaldness moving bed biofilm process. Aquacultural Engineering 34:322–331.

Rusten, B., L. J. Hem, and H. Odegaard. 1995. Nitrification of municipal wastewater in moving-bed biofilm reactors. Water Environment Research 67(1):75–86.

Summerfelt, S. T. 2006. Design and management of conventional fluidized-sand filters. Aquacultural Engineering 34:275–302.

Summerfelt, S. T., J. Davidson, T. Waldrop, S. Tsukuda, and J. Bebak-Williams. 2004. A partial reuse system for coldwater aquaculture. Aquacultural Engineering 31:157–181.

Summerfelt, S. T., M. Sharrer, M. Gearheart, K. Gillette, and B. J. Vinci. 2009. Evaluation of partial water reuse systems used for Atlantic salmon smolt production at the White River National Fish Hatchery. Aquacultural Engineering 41:78–84.

Thomasson, M. P. 1991. Nitrification in fluidized bed sand filters for use in recirculating aquaculture systems. Unpublished Master's thesis, Louisiana State University, Baton Rouge, LA, USA.

Timmons, M. B., S. T. Summerfelt, and B. J. Vinci. 1998. Review of circular tank technology and management. Aquacultural Engineering 18(1):51–69.

Van Gorder, S. D. and J. Jug-Dujakovic. 2004. Performance characteristics of rotating biological contactors within a commercial recirculating aquaculture system. Pages 350–360 *in* Proceedings of the Fifth International Conference on Recirculating Aquaculture, July 22–24.

Watanabe, W. O. 1995. Aquaculture of the Florida pompano and other jacks (Family Carangidae) in the Western Atlantic, Gulf of Mexico, and Caribbean basin: status and potential. Pages 185–205 *in* K. L. Main and C. Rosenfeld, editors. Culture of high-value marine fishes. Oceanic Institute, Honolulu, Hawaii, USA.

Weirich, C. R., D. R. Groat, R. C. Reigh, E. J. Chesney, and R. F. Malone. 2006. Effect of feeding strategies on production characteristics and body composition of Florida pompano reared in marine recirculating systems. North American Journal of Aquaculture 68(4):330–338.

Weirich, C. R., P. S. Wills, R. M. Baptiste, P. N. Woodward, and M. A. Riche. 2009. Production characteristics and body composition of Florida pompano reared to market size at two different densities in low salinity recirculation aquaculture systems. North American Journal of Aquaculture 71(2): 164–172.

Wheaton, F. W., J. N. Hochheimer, G. E. Kaiser, R. F. Malone, M. J. Crones, G. S. Libey, and C. E. Easter. 1994. Nitrification filter principles. Pages 101–126 *in* M. B. Timmons and T. M. Losordo, editors. Aquaculture water reuse system: engineering design and management, volume 27. Elsevier, New York, New York, USA.