Utilization of a zero-exchange, mixed-cell raceway for marine shrimp production

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1.0 Introduction

The use of the zero-exchange systems has become a viable alternative to traditional pond methods of intensive aquaculture production. Recently, the concept of zero-exchange systems has been applied to indoor tank based production systems for marine shrimp, *Penaeus vannamei*. In these systems, ammonia-nitrogen is controlled by the manipulation of the carbon/nitrogen ratio in such a way as to promote the growth of heterotrophic bacteria (Avnimelech, 1999, McIntosh, 2001). As a result, the ammonia-nitrogen is removed from the system through assimilation into microbial biomass. As a bonus, for some aquaculture species (marine shrimp and tilapia), this bacterial biomass produced in the intensive zero-exchange systems can be an important source of feed protein, reducing the cost of production and thus improving the overall economics (Moss, 2002).

Raceways have been used for years for the production of salmonids and other species by federal and state agencies for stocking purposes and commercial growers. Where there are large ground water resources, raceways are the most common rearing tank design being used to grow the majority of rainbow trout produced in the USA. One significant advantage of raceways is their better utilization of floor space and easier handling and sorting of fish as compared to circular tanks. Their primary disadvantages are the large volume of water required for maintaining water quality and their limited self-cleaning ability (Timmons et al. 1998). Water enters the raceway at one end and flows through the raceway in a plug-flow manner. As a result, the best water quality is found at the head of the raceway where the water first enters and then it deteriorates steadily towards the raceway outlet. Because of the low velocities through the raceway (2-4 cm/s), removal efficiency of settled solids is very poor, requiring frequent cleaning and maintenance tasks (Timmons et al. 1998). This is due to the hydraulic design being based on oxygen design requirements, rather than cleaning requirements, that result in the much lower
velocities. In practical terms, raceways are incapable of producing the optimum water velocities recommended for fish health, muscle tone, and respiration (Timmons et al. 2002). Even using lower exchange rates and lower velocities, use of raceways is being severely limited due to the unavailability of large quantities of high quality water, increased concern about their environmental impacts on receiving waters, and the difficulty in treating the large flows producing a large effluent discharge. One solution to this problem is to convert raceways into a series of counter-rotating mixed-cells (Watten et al. 2000). The concept of a mixed-cell raceway was first proposed by Watten et al. (2000) to eliminate metabolite concentration gradients, increase current velocities, and improve solids scour at low water exchange rates. Watten modified a standard raceway section 14.5 m long and 2.4 m wide by creating a series of six counter-rotating cells, each 2.4 m by 2.4 m. A series of vertical pipe sections with jet ports were installed in the corners of each cell and water directed tangentially to create rotary circulation. Water was withdrawn from centrally located floor drains.

Figure 1. Prototype mixed-cell raceway, 16.3 m x 5.44 m x 1.22 m (Watten et al. 2000).

A prototype mixed-cell raceway was constructed and designed to operate as a series of square/octagonal tanks, each having a center drain for continuous removal of solids and sludge. In 2004, the system was stocked with marine shrimp, *Penaeus vannamei* and managed as a zero-exchange low salinity production system for several months. Research was conducted into new methods of maintaining or controlling the dynamics of the water quality of the system through the addition of carbon to stimulate heterotrophic bacterial production (Ebeling et al. 2006). In addition, suspended solids concentration in the production tank was maintained at acceptable levels by controlling the amount and frequency of discharge from the settling tank. This paper briefly reviews the design concepts of a mixed-cell raceway and presents some results of the research trial.
2.0 Design

The basic design concept of the mixed-cell raceway is to operate it as a series of adjacent counter rotating square/octagonal tanks, each having a center drain for continuous removal of solids and sludge, Fig. 2. Early research on mixed-cell raceways by Watten et al. (2000) examined their use in retrofitting existing raceways at federal and state hatcheries and was reflected in the overall small systems size, 22.7 m$^3$. In contrast, our research started with the design of a small commercial production system, 108 m$^3$. In addition, Timmons, et al. (1998) recommended tank diameter to depth ratios for good self-cleaning capability from 5:1 to 10:1, compared to 3.7 for Watten et al. 2000 vs. 5.5 in this current study.

2.1 Mixed-cell raceway

A prototype raceway was constructed in an existing greenhouse with approximated dimensions of 16.3 m x 5.44 m x 1.22 m (54 ft x18 ft x 4 ft), which created three mixed-cells (Ebeling, et al. 2005). The basic design concept was to operate the raceway as a series of square/octagonal tanks, each having a center drain for continuous removal of solids and sludge. Each cell received water from four vertical manifolds (downlegs) extending to the raceway floor and located in the corners of each cell and at the intersection between adjacent cells (Fig. 3); four of the manifolds supply water to two cells concurrently. Water is pumped through several orifice discharges (or jet ports) from each of the downleg pipes to establish rotary circulation in the cell, with adjacent cells rotating in opposite directions. Each cell had a bottom drain located at the center of the cell connected to a drain line, which discharged solids and sludge to a settling sump.
Figure 3. Cross-section of mixed-cell raceway showing construction details, pipe manifolds, vertical manifolds and drain details.

This was then combined with the concept of the ‘Cornell double drain system’, where 10% to 20% of the total flow into a tank was removed from a center bottom drains and 80 to 90% of the flow was removed from the side drains (Timmons et al. 1998). Settable wastes and sludge were then removed from the center drains and collected in a settling sump.

2.2 Orifice Design

Labatut et al. (2006) conducted a series of experimental trials to evaluate the effect of nozzle diameter and the rate of bottom-center drain discharge on both the magnitude and uniformity of rotational velocities in the mixed-cell. Three nozzle diameters, 10, 15, and 20 mm, and three bottom-center flows, 0, 15, and 20%, were evaluated. Measurements of rotational velocities in the mixed-cell were made at 5 cm from the bottom of the tank. While the nozzle diameter was found to have a highly significant influence (p < 0.01) on the magnitude of the rotational velocities, the percentage of bottom flow did not (p > 0.05). Also, results suggested that uniformity of rotational velocities in terms of the radial-wise profile is not affected by either the nozzle diameter or the percentage of bottom flow.

Labatut et al. (2006) also showed that the flux of momentum is the driving force controlling rotational velocities in a jet-forced circulation vessel and therefore jet velocity and nozzle diameter become the main variables to control. He found that the linear influence of the jet velocity on rotational velocities reported in previous studies remained valid provided that the nozzle diameter was maintained constant. Results of the study indicated that rotational velocities in mixed-cells follow a logarithmic trend as a function of the nozzle diameter for a constant jet velocity. The linear and logarithmic models were combined to construct a set of iso-curves to predict rotational velocities as a
function of jet velocity and nozzle diameter (Fig. 4). The iso-curves can be used to facilitate the design of a MCR where particular rotational velocities are desired.

![Iso-curves for predicting mean rotational velocities for different nozzle diameters and discharge jet velocities. Plot was based on bottom rotational velocities obtained in bottom flow rates that varied from 0 to 20%, a water depth of 1.15 m, and a mixed-cell diameter-to-depth ratio of 4.8:1. (From Labatut, et al. 2006)](image)

**Figure 4.** Iso-curves for predicting mean rotational velocities for different nozzle diameters and discharge jet velocities. Plot was based on bottom rotational velocities obtained in bottom flow rates that varied from 0 to 20%, a water depth of 1.15 m, and a mixed-cell diameter-to-depth ratio of 4.8:1. (From Labatut, et al. 2006)

In a zero-exchange system, ammonia-nitrogen is removed via the growth of heterotrophic bacteria, stocking densities are low (5 to 10 kg/m$^3$) and oxygen requirements are modest, so high tank exchange rates through biofilters and oxygenators are not necessary. At an exchange rate of approximately 0.5 tank volume/hr, a flow rate of only 0.74 m$^3$/min (250 gpm) is required for the raceway in this example. This was accomplished using two 0.95 kW (1 hp) pumps which removed water at the two ends of the raceway and injected it into a 7.5 cm (3 in) manifold that circled the top of the raceway. Water was withdrawn either from a 5 cm (2 in) PVC pipe inlet located approximately 25 cm below the surface at one end or an end sidewall discharge drain at the other. Approximately 15% of the flow 0.13 m$^3$/min (35 gpm) was from the three bottom drains, using a smaller 0.375 kW (1/2 hp) submersible pump in the sump drain.

Little is know about the optimal tank rotational velocities for marine shrimp. A mean tank velocity of 10 cm/s was chosen to insure adequate rotational velocities to move waste particles and uneaten food to the center drains. From Fig. 3, the required discharge jet velocity for a tank mean rotational velocity of 10 cm/s is approximately 4 m/s. The required piezometric head to achieve this jet velocity is computed from the equation described by Brater and King (1976):
\[ V_o = C_d \sqrt{2 \cdot g \cdot h} \]  

where,

- \( V_o \): Nozzle discharge velocity or jet velocity (m/s)
- \( C_d \): Coefficient of Discharge of the nozzles (0.93, dimensionless)
- \( g \): Acceleration due to gravity (9.81 m/s\(^2\))
- \( h \): Piezometric head, i.e., pressure head upstream of the nozzle (m)

The \( C_d \) of the nozzles was obtained from a series of flow rate measurements in four jet port manifolds at different piezometric heads. Details of the experiment and data are given by Labatut (2005). The average \( C_d \) reported by Labatut was consistent with the values found in literature for this kind of entrance (Brater and King, 1976). By using Equation (1), a jet velocity of 4.0 m/s, and a \( C_d \) of 0.93, the required piezometric head was calculated to be 1.0 m.

A requirement of the system design was to maintain a water exchange rate of 0.5 volumes per hour, i.e., a total system flow rate of 0.74 m\(^3\)/h. In order to keep a constant jet velocity and flow rate, Equation (1) can be modified to include the nozzle flow rate and nozzle cross-sectional area and solve for the required nozzle diameter:

\[ Q_o = A_o \cdot C_d \sqrt{2 \cdot g \cdot h} \]  

with

\[ A_o = \pi \frac{D_o^2}{4} \]  

where,

- \( Q_o \): Nozzle discharge flow rate (m\(^3\)/s)
- \( A_o \): Nozzle cross-sectional area (m\(^2\))
- \( D_o \): Nozzle diameter (m)

The calculated nozzle flow rate is \(1.48 \times 10^{-2} \) m\(^3\)/s, as obtained by dividing the total flow rate by 50, which was the number of nozzles in the prototype mixed-cell raceway water distribution system. Also, to keep the jet velocity constant at 4.0 m/s, the piezometric head computed in the previous step (1.0 m) was used. Finally, the only unknown term remaining in Equations (2) and (3) is the nozzle diameter, which can then be explicitly determined and was found to be approximately 10 mm.
3.0 Results

A SonTek Argonaut Acoustic Doppler Velocimeter from Yellow Springs Instruments (1725 Brannum Lane, Yellow Springs, OH 45387 USA) was utilized in this study to measure speed and direction within the hydraulically separated cells. The SonTek velocity meter is a single-point, 3D Doppler current meter that measures water velocity via the Doppler shift in frequency of sound from a moving object, in this case small particulate matter in water current. The SonTek probe assembly was mounted on a rigid aluminum beam supported above the width of the raceway, which allowed the probe to be moved across the raceway width in a repeatable fashion. The probe was lowered into the raceway to specified depths of 5 cm off the bottom, mid-depth, and 10 cm below the water surface, along a 0.5 m horizontal-squared-grid measuring system. Measurements were taken for a 20 seconds averaging interval at each of grid points and the values averaged for a numerical value used to plot the results. The data collected form the SonTek system was downloaded into Microsoft Excel for processing and contour graphing of the velocities was created with Sigma Plot.

Figure 5 shows the contour plot for cell #3 (end cell) at velocity intervals of 5 cm/sec, approximately 5 cm off the bottom. The pressure head was approximately 1.00 m gauge (1.5 psi). As can be seen in this figure, relatively high scouring velocities are found at the outside perimeter of the cell (20 to 24 cm/sec), lower velocities near the center (10 to 6 cm/sec) and very low velocities at the center of the cell. The velocity profiles shown in Figure 6 were created by averaging the velocities at each grid point in an annular ring 0.5 m wide starting at the center at each of the three depths. This graph shows the almost linear velocity profile as a function of distance from the center drain and significant cleaning velocities in the corners of the cell. The velocities in the z-direction were very small, just above the drain values of -2.2 to 2.8 cm/s was measured. The mean tank rotational velocity was estimated from the average of all measurements taken as 10.5 cm/s, consistent with both the initial assumption and Fig. 4.
Figure 5. Velocity contour plot for cell #3, with 10 mm orifice diameter, 100 cm pressure head, recirculating 250 gpm or approximately 0.5 tank exchanges/hr and 15% withdrawal from the center drains.

Figure 6. Cell #3 mean velocity profile with 10 mm orifice diameter, 100 cm pressure head, recirculating 250 gpm or approximately 0.5 tank exchanges/hr and 15% withdrawal from the center drains.
2.3 Solids Management

During the demonstration zero-exchange production trial, the mixed-cell raceway received from 4 to 5 kg of feed per day, plus supplemental carbon in the form of sugar. Figure 7 shows the daily sludge removed from the sludge tank during this production trial. Daily removal rates of uneaten feed, fecal matter, and excess heterotrophic bacterial floc ranged from 1 to 8 kg dry weight per day, demonstrating the solids removal effectiveness of the mixed-cell raceway.

![Figure 7. Solids removed by settling tank for demonstration zero-exchange marine shrimp production, 4 to 5 kg feed per day.](image)

5.0 Conclusions

In order to better understand the hydraulics of a large, mixed-cell raceway, a prototype raceway was constructed in an existing greenhouse. The prototype raceway was constructed of simple, readily available materials at a low economic cost, allowing for rapid start-up (or shut down) of production systems. Results of this study showed excellent bottom velocities for scouring solids and moving them towards the center drains in each cell of the prototype mixed-cell raceway. Mixed-cell raceways show excellent potential for either retrofitting existing raceways or as a design for a new production system.

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