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Performance of single-drain and dual-drain tanks in terms of water velocity profile and solids flushing for *in vivo* digestibility studies in juvenile shrimp

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ABSTRACT

In vivo digestibility determination in shrimp is a challenge because these animals are coprophagous, benthic and slow feeders and the small amount of feces that they produce is difficult to collect. The objective of this study was to evaluate an efficient tank design for the purpose of studying shrimp digestibility. Different tank designs were evaluated considering drain system (dual-drain and single-drain), water inlet flow rate (8, 12, and 16 L min^{-1}) and bottom drain diameter (6, 13, 19, 25 and 50 mm) and their effects on tank hydraulics, water velocity and solids flushing. A circular and slightly conical 500 L tank was adapted with a clarifier for the two dual-drain designs (Cornell-type and central-type) and settling columns for the two single-drain designs (Guelph-F and Guelph-L). Results showed that: (1) water rotational velocity profile was more homogeneous in tanks with larger bottom drain outlets, and water velocity increased with water inlet flow rate from almost zero up to 14.5 ± 0.7 cm s^{-1}; (2) solids flushing, measured as the percentage of feed pellets retained at both the bottom drain and in the settling devices, was positively correlated with the surface loading rate (L min^{-1} flow per m^2) and was more effective at the Guelph-L design fitted with a 150 mm diameter settling column. In this system 100% of the solids were removed at the inflow rate of 16 L min^{-1}. It can be concluded that among the systems evaluated, the Guelph-L at an inflow-rate of 12 L min^{-1} was most efficient for both solids removal and water velocity profile and thus seemed more suitable for shrimp digestibility studies in high performance conditions. Technologies involving hydrodynamic must be intensively applied to solids removal for aquatic species production as well as research purposes like digestibility, which is highlighted in this study.

1. Introduction

Digestibility measurements are a key component when evaluating quality of feed ingredients for nutrition studies. Typically, indirect methods employing dietary markers are used for digestibility measurements in shrimp when maintained in tanks of varying dimensions and shapes. Their feces are collected either by siphoning or by sedimentation within a water column (Cho and Slinger, 1979; Forster et al., 2003; Smith and Tabrett, 2004).

The reported tank volumes for shrimp apparent digestibility studies varied from 20 to 500 L. These are usually rectangular or cylindrical with a flat or slightly conical bottom (Smith et al., 2007; Glencross et al., 2002; Cruz-Suárez et al., 2007; Forster et al., 2003). The large variety of systems and procedures makes it difficult to compare the results and their efficiency in terms of solids or feces removal. Moreover, the diversity of experimental conditions, including feed manufacture and rearing conditions and procedures, creates concerns about the variability of data. Some authors have emphasized the importance of stable environment to minimize shrimp stress as well as optimize nutrients so as to attain maximum growth of experimental animals (Tacon, 1996; D'Abramo and Castell, 1997; Smith and Tabrett, 2004; Glencross et al., 2007).

Compared to most fish species, *in vivo* digestibility determination in shrimp is more challenging because of their benthic behavior which makes it difficult to use conical shaped tanks. Being slow feeders and coprophagous, the removal of feed and feces is complicated, resulting in nutrients rapidly leaching from the feed and feces thus altering the marker to nutrient ratio compromising the quality and the sampling efficiency of the shrimp feces. The technique of

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collecting feces by siphoning, aside from being labor intensive may be criticized for potential undesirable effects upon animal welfare, and as such non-compatible to practical rearing conditions (Tacon, 1996; D'Abramo and Castell, 1997).

There are few studies regarding the design of tanks for aquatic animal rearing. Most of the ones for shrimp have been focused on production (Freeman and Duerr, 1991; Tseng et al., 1998) except for the study of Kumaraguru vasagam et al. (2009) which evaluated a self-cleaning mechanism in a microcosm tank.

In the aquaculture engineering field, numerous studies have focused on solids removal within culture systems. This is important because the fecal matter, uneaten feed, and feed fines can be broken rapidly into much finer particles due to water turbulence, animal motion, scouring, and pumping making it much more difficult to remove fine particulate matter than larger particles (Summerfelt et al., 2000).

The use of clarifiers and swirl separators (also known as Hydrodynamic Vortex Separators – HDVS) is an efficient method for solids removal within fish tanks. Swirl separators have already been used for different applications such as urban drainage systems, water quality control, mineral industry and wastewater treatment (Andoh and Saul, 2003; Vinci et al., 2004; Veerapen et al., 2005).

The tank hydraulics impact directly on the water circulation profile, which in turn increases the solids discharge through the mass displacement from the periphery to the center of the tank and then to the settling device. Knowledge of the factors behind the tank hydraulics, as explored in the studies conducted by Davidson and Summerfelt (2004) and Labatut et al. (2007) together with different solids removal technologies provided an important insight on the application of new concepts into the aquaculture nutrition studies reducing the gap between the laboratory and the practical conditions. This is important if these data are to be applied to practical farm conditions (Tacon, 1996).

The objective of this study was to develop a system to study *in vivo* shrimp digestibility which would combine efficient solids removal, reduced stress and optimize shrimp performance. This study evaluated the effect of system design (dual-drain *versus* single-drain), inflow rate, and secondary drain diameter on the tank hydraulics, water velocity profile and solids flushing efficiency (corresponding to the feed removal efficiency).

2. Materials and methods

2.1. System design and hydraulics

Hydraulics, water velocity profile and solids flushing were evaluated using two settling tank designs and modifications: (1) dual-drain tanks (Cornell-type dual-drain and central-type dual-drain); (2) single-drain tanks (Guelph settling tank design adapted by Forster et al. (2003) – Guelph-F, and the Guelph tank settling design adapted by Lee (2002) – Guelph-L) (Fig. 1).

Three inflow rates (8, 12 and 16 L min^{-1}) and three secondary drain diameters were adopted using polyethylene hose with diameters of 6.0, 12.7 and 19.1 mm for the dual-drain tanks. PVC pipe diameters were 25 and 50 mm for the Guelph-F and 50 mm for the Guelph-L. A total of 27 treatments were run in triplicate.

A single 500 L circular and slightly conical tank made of reinforced fiberglass was modified to evaluate all designs and modifications. The tank frustum measured 1000 and 960 mm (superior and inferior diameters) and 670 mm height. The bottom sloped 5° toward the drain that measured 170 mm × 50 mm × 65 mm (upper and lower diameter plus height, respectively). The bottom drain assembly was the same for all tanks. The internal surface finish was a gel coat application and smooth polishing (Figs. 1 and 2).

The depth of the water in the tanks was 400 mm giving a volume of 0.4 m^3 (tank diameter to water depth ratio of 2.5). The Cornell-type tank was provided with two drains. A primary drain consisting of a 60 mm PVC pipe laminated to the side-wall at 450 mm from the tank bottom. A secondary drain consisting of a 15 mm PVC pipe was laminated in the bottom drain area tangentially to the bottom drain wall. This secondary drain was at a 2° downward angle oriented counter-clockwise (Fig. 1).

The bottom drain of the Cornell-type tank was covered with a 170 mm diameter plate in order to simulate an access barrier of the shrimp into the drain. It was fixed to a 50 mm diameter pipe by an

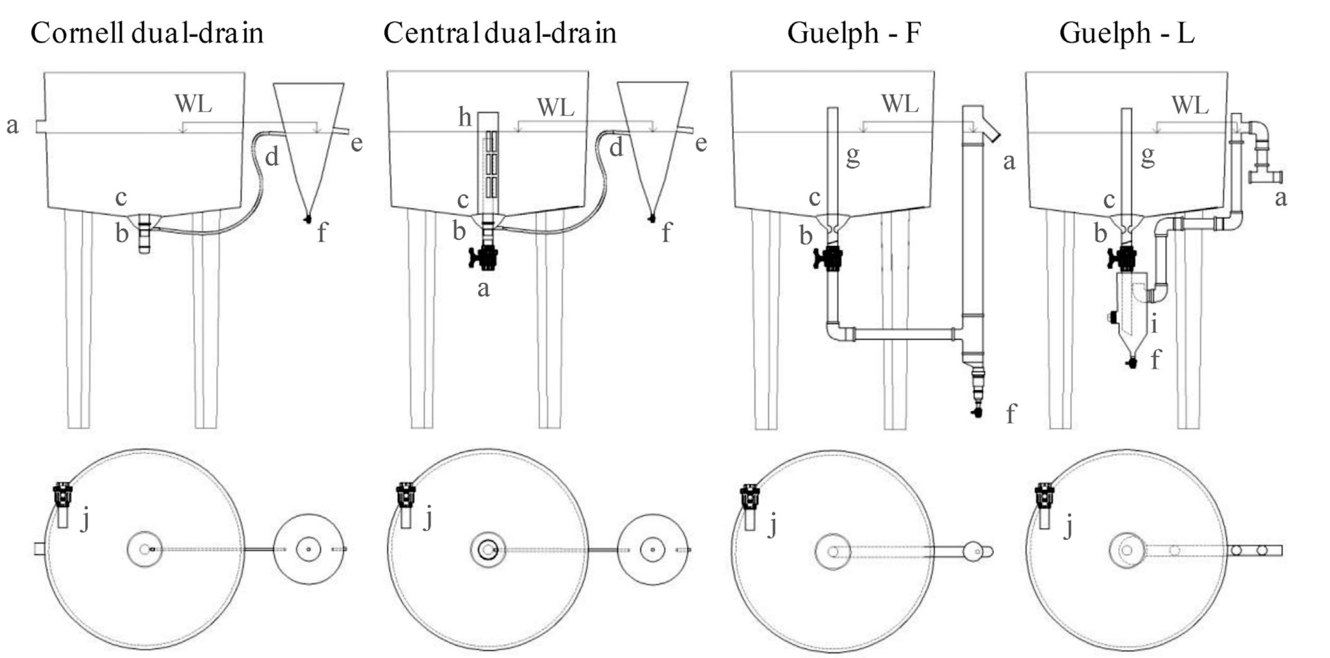

Fig. 1. Plan and section view of the Cornell dual-drain, central dual-drain, Guelph-F and Guelph-L tanks inlet and drains evaluated for digestibility studies with shrimp juveniles. (a) Primary drain (or single drain), (b) secondary drain, (c) cover plate, (d) clarifier inlet, (e) clarifier outlet, (f) outlet for sampling and solids removal, (g) stand pipe (loose pipe), (h) outer screen, (i) settling column, (j) water inlet. WL – water level.

adapter to fit into the bottom sleeve and spaced about 5 mm above the tank bottom allowing passage of feed particles (Fig. 1).

In the central-type tank a 50 mm × 440 mm (diameter and height, respectively) standpipe was fitted to the bottom drain for the primary drain. A 100 mm × 540 mm (diameter and height, respectively) pipe with oblong holes of 5 mm × 100 mm was placed as an outer screen and laminated to a 170 mm diameter cover also spaced about 5 mm above the tank bottom. The secondary drain and cover plate assembly was identical to the one previously described for the Cornell-type tank (Fig. 1).

The clarifier assessed in the dual-drain trials had an internal volume of 23 L. It measured 480 mm × 352 mm × 122 mm (height, superior diameter and inferior diameter) in the frustum, 160 mm × 122 mm × 15 mm (height, superior diameter, inferior diameter) in the cone. A 15 mm ball valve was coupled at the bottom of the cone to remove the settled solids. The inlet and outlet pipes (diameters of 15 mm and 25 mm, respectively) were positioned 250 and 245 mm below the border, respectively, and oriented 5° downward enhancing the gravitational settlement through the use of a rotating flow field that reduces turbulence (Fig. 1).

For the Guelph-F tank, the settling column of 1400 mm (height) × 100 mm (diameter) ended in a 100 mm × 50 mm eccentric reducer coupling fitted to a sleeve and a 50 mm × 20 mm reducer coupling and a 20 mm ball valve for solids removal. A reducing tee of 100 × 50 mm above the eccentric reducer coupled with a 50 mm PVC pipe and a 90° elbow connected the settling column to the bottom of the tank through a 50 mm ball valve (Fig. 1).

The Guelph-L column was fixed to the tank drain by a 50 mm × 50 mm PVC pipe beveled at its upper end which was glued to the bottom drain sleeve. The other end was glued to a 50 mm ball valve fixed to the Guelph-L column (300 mm × 150 mm in the trunk and 100 mm × 150 mm × 20 mm in the cone). The water with solids flows through a guide pipe directing the solids to the cone. The cleaner water leaves the column through a 50 mm elbow laminated in its superior part with its opening turned upwards to avoid the solids being carried away with the stream. A 60 mm adapter with a plug was laminated into the column to allow access for cleaning purposes (Fig. 1).

For the Guelph tanks, a fiberglass 170 mm diameter top plate was laminated onto a loose 50 mm × 70 mm pipe beveled at the inferior end. This loose pipe could be rotated on top of the beveled end of the glued pipe to adjust the space between its plate and the bottom drain set to about 5 mm. The loose PVC pipe part inside the drain had three 45 mm oblong holes below its plate which are level to the bottom drain. These allowed the flow of solids from the drain to the settling column (Fig. 2).

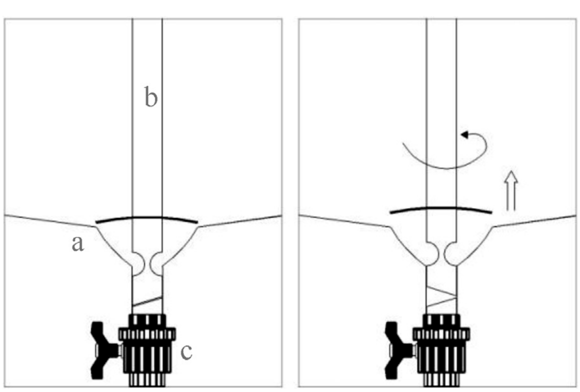

Fig. 2. Detail of the bottom drain (a), loose pipe with top plate (b) and ball valve (c) adapted to the Guelph tanks. At the position 1 top plate closes the bottom drain. At the position 2 top plate is spaced about 5 mm above the bottom floor.

Trials were performed without animals. For the dual-drain, all tank layouts were assessed in separate. The same source of fresh water supplied to all tanks. A 6.0 m hydraulic head relative to the tank surface was maintained. A counter-clockwise inflow supplied fresh water through a 300 mm × 25 mm (length and diameter) open pipe parallel to the tank floor and the tank wall (Fig. 1). The water flow was measured using a calibrated bucket and a stop watch (Summerfelt et al., 2000).

The hydraulics issue was evaluated in terms of hydraulic exchange time (HET) through the tank that means the time required to exchange the volume of a tank, percent of water flow through the bottom drain and surface loading ratio (L min^{-1} per m^2 tank floor area).

2.2. Water velocity measurements and shrimp behavior

The water velocity was measured by timing the distance traveled by a neutral buoyancy object transported unobstructed by the rotating water flow at a given distance (approximately 2, 20 and 40 cm) from the tank wall (outer, middle and inner perimeters) (Davidson and Summerfelt, 2004). A ruler was used as a guide and care was taken not to interfere with the object's trajectory and velocity. Velocity measurements at the tank perimeters defined an 8 min interval to be acceptable to achieve steady state. To avoid interference on solids displacement, all debris or sand was removed from the tank floor before each test.

Measurements were taken in triplicate and in relation to a mark on the tank border. The water velocity (V) was calculated dividing each one of the outer, middle and inner perimeters by the time elapsed for a complete round of the floating object, according to the following formula (1):

$$V = \frac{2\pi r}{t} \tag{1}$$

where π is the constant, r is the radial position of the floating object at the outer, middle and inner perimeters, which was 0.51 m, 0.25 m and 0.13 m, respectively, and t is the time.

A complementary test to investigate the effect of the water velocity on the shrimp behavior was performed in a central-type dual-drain tank stocked with 43 juveniles (60 m^{-2}) *Litopenaeus vannamei* (8 g mean individual weight). Seawater of 35‰ and 29 °C was supplied at the inflow rates of 8, 12 and 16 L min^{-1}.

2.3. Solids flushing efficiency measurement

The efficiency of solids removal in terms of pellets flushing was evaluated in triplicate after the water steady state had been achieved. Twenty shrimp feed pellets (Guabi Vannamei 35% CP, extruded, measuring 4.60 ± 0.68 mm length and 2.49 ± 0.20 mm diameter, a bulk density of 1159.31 ± 176.27 and a surface:volume ratio of 0.22 ± 0.02) were added about 15 cm behind the water inlet, siphoned 5 min afterwards and counted. After each measurement the tank was flushed to remove any particles remaining in the bottom drain and new feed pellets were used.

The number of pellets retained in the settling devices, *i.e.* clarifier or settling column, was also counted. The solids removal efficiency was calculated in terms of percentage of pellets in the bottom drain (P_{drain}) and pellets retained in the settling device (P_{SetDev}), according to formulae (2) and (3):

$$P_{\text{drain}} = \left(20 - \frac{n_{\text{b}}}{20}\right) \times 100 \tag{2}$$

where n_{b} is the number of pellets in the tank bottom.

$$P_{\text{SetDev}} = \left(\frac{n_{\text{s}}}{20}\right) \times 100 \tag{3}$$

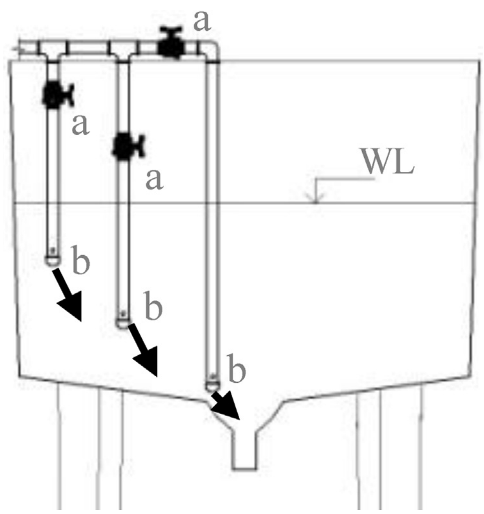

Fig. 3. Three stage water inlet adapted in a central-type tank for the evaluation of solids flushing for digestibility studies with shrimp juveniles. (a) 25 mm ball valve and (b) 8 mm opening. Arrows indicate the water inlet jet orientation.

where n_s is the number of pellets retained in the settling device.

It is important to emphasize that these parameters indicate the efficiency of the tank and settling device combined.

Two additional tests evaluated the effect of a secondary drain pipe angled in relation to the bottom drain wall: 0° and 90° and the effect of the water from a three stage water inlet in the central dual-drain tank in comparison to the open pipe inlet (inflow rate of 12 L min^{-1} and 12.7 mm secondary drain diameter). The three-stage water inlet consisted of one horizontal pipe (500 mm × 25 mm) perpendicular to the tank wall. It had three 25 mm diameter vertical pipes of 410, 540 and 670 mm × 25 mm lengths ending in 8 mm openings. Each pipe had an individual ball valve and a capped end. Water was injected at depths of 100, 230 and 370 mm below the surface and at distances of 70, 220 and 410 mm from the tank wall with the aim of improving the water velocity profile and the mass flow in the inner perimeter of the tank thus increasing the feed flushing speed (Fig. 3).

2.4. Statistical analysis

Three-way and a two-way ANOVAs were performed to test data differences for water velocity and pellets flushing efficiency in relation to the tank design, inflow rate and secondary drain diameter in dual-drain tanks and in relation to the tank design and inflow rate in single-drain tanks, respectively. Statistically significant differences between the efficiency of pellets flushing within treatments were determined using Tukey's HSD test (Zar, 2000). STATISTICA® 9.0 (StatSoft) was used for all statistical analysis. Effects were considered significant at $P < 0.05$.

3. Results and discussion

3.1. Hydraulics

The hydraulics of the tanks in this study varied according to their designs. The readings showed small variations in the sum of the primary and secondary outflows, probably due to small fluctuations in the inflow rate. A larger variation was noticed in the sum of the outflows of the dual-drain tanks (19.1 mm secondary drain, inflow rate of 8 L min^{-1}) which is a result of a smaller resistance in the outlet line combined with a small water inflow (Table 1).

Although the diameter to depth ratio of the tanks (2.5) was slightly smaller than the range of 3–5 recommended for efficient water mixing in finfish tanks (Timmons and Ebeling, 2007) it was within the range reported in other studies with shrimp in experimental tanks (1.06–1.16, Freeman and Duerr, 1991; 3.54, Barón et al., 2004; 1.42, Kumaraguru vasagam et al., 2009; 4.71, Ray et al., 2010). It also seemed adequate for the purpose of this study that no crowding of animals or poor solids removal was noticed because the small size of the tank was sufficient for efficient water mixing. The hydraulic exchange time (HET) (Table 1) was above the 10 min suggested for small tanks (<1 m^3) stocked with fish (Timmons and Ebeling, 2007). Although smaller hydraulics exchange times are desirable for carrying more dissolved oxygen into the tank they can affect the shrimp performance due to the energy expenditure needed to cope with strong water currents.

In the dual-drain tanks, the flow rate in the secondary drain increased with the secondary drain diameter regardless of the inflow rate. The flow of the secondary drain is only a function of the resistance in the outlet line and the pressure drop across that line. This pressure stayed constant as the water level in the tank did not vary when the inlet flow rate was changed. As expected, the percentage of the outflow through the secondary drain diminished with inflow rate and increased with the bottom drain diameter. These values ranged from 7.3% in the 6 mm drain diameter (at the inflow of 16 L min^{-1}) to 100% in the 19 mm drain (inflow rates of 8 and 12 L min^{-1}) indicating that the secondary drain diameter was oversized for those inflow rates and as a result all the outflow occurred through the secondary drain (Table 1, Fig. 4).

The main advantage of the dual-drain tanks in recirculating aquaculture systems (RAS) is the removal of the largest fraction of suspended solids. They become concentrated in a small stream of water of 5–20% of the total outflow, thus reducing the water volume for further treatment (Cripps and Bergheim, 2000; Davidson and Summerfelt, 2005; Timmons and Ebeling, 2007). The outflow rates within this range were achieved in the dual-drain tanks with the secondary drain of 6 mm with the three inflow rates. It did not necessarily result in a more efficient solids removal.

In the dual-drain tanks the 6 mm secondary drain diameters limited the mass flow through the bottom drain resulting in a surface loading rate below the recommended (5–6 L min^{-1}) for optimum solids flushing hydraulics (Davidson and Summerfelt, 2004) in contrast to the tanks with larger drains (Table 1 and Fig. 4). The higher the surface loading rate the better the solids flushing.

3.2. Water velocity

In the dual-drain tanks, water velocity profiles (measured in the inner, middle and outer perimeters) were significantly affected by the system, inflow rate and secondary drain diameter and all these factors interacted ($P < 0.001$). In the Guelph tanks the water velocity was significantly influenced by the inflow rate only ($P < 0.001$) (Fig. 5).

The water velocity profiles in all tanks within each system showed non-uniform velocities that increased almost linearly with radial distance from the tank center, possibly as a result of the open-end pipe water inlet that injected the water in a single point of the tank (Fig. 5). In a 9.1 m diameter finfish tank water velocities of almost zero were reported close to the center of the tank while near the tank wall the velocity was about 40 cm s^{-1} (Summerfelt et al., 2006).

A critical water velocity of 6 cm s^{-1} in the middle area of the tank was established to be the optimum for shrimp welfare, energy expenditure and for efficient solids removal. At 75% of this velocity mobilization of reserves of juvenile *L. vannamei* swimming against the current begins (Zhang et al., 2006) and is slightly lower than the value of 7–8 cm s^{-1} reported in a previous study (Freeman and Duerr, 1991).

Table 1
Hydraulics, operation parameters and performance of the four systems comprising system type, drain diameters and inflow rates for the evaluation of the water velocity profile and solids flushing in single drain and dual drain tanks for the determination of the digestibility with shrimp juveniles.

	System														
	Cornell-type dual drain									Central-type dual drain					
Parameter/inflow rate (L min^{-1})	8.0	12.0	16.0	8.0	12.0	16.0	8.0	12.0	16.0	8.0	12.0	16.0	8.0	12.0	16.0
Primary/single drain tube diameter (mm)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	50.0	50.0	50.0	50.0	50.0	50.0
Hydraulic exchange time (HET) (min)	50.0	33.3	25.0	50.0	33.3	25.0	50.0	33.3	25.0	50.0	33.3	25.0	50.0	33.3	25.0
Flow rate at the primary/single drain (L min^{-1})	7.4	11.5	15.5	2.8	5.9	10.5	0.0	0.0	2.3	7.2	11.6	15.2	1.9	6.9	10.3
Secondary drain diameter (mm)	6.0	6.0	6.0	12.7	12.7	12.7	19.1	19.1	19.1	6.0	6.0	6.0	12.7	12.7	12.7
Flow rate at the secondary drain (L min^{-1})	1.2	1.4	1.2	6.2	6.3	5.6	12.0	12.9	13.7	1.2	1.3	1.2	5.7	6.1	6.4
Percent of total tank flow discharged through secondary/single drain as % of total tank outflow	14.1	10.5	7.3	68.9	51.9	34.8	100.0	100.0	85.8	14.1	9.8	7.5	75.2	46.9	38.4
Surface loading rate discharged through secondary /single drain (L min^{-1}) flow per m^2 tank floor area	1.7	1.9	1.7	8.7	8.9	7.9	16.9	18.2	19.3	1.7	1.8	1.7	8.1	8.6	9.0

	System											
	Central-type cont.			Guelph-F						Guelph-L		
Parameter/inflow rate (L min^{-1})	8	12	16	8	12	16	8	12	16	8	12	16
Primary/single drain tube diameter (mm)	50.0	50.0	50.0	25.0	25.0	25.0	50.0	50.0	50.0	50.0	50.0	50.0
Hydraulic exchange time (HET) (min)	50.0	33.3	25.0	50.0	33.3	25.0	50.0	33.3	25.0	50.0	33.3	25.0
Flow rate at the primary/single drain (L min^{-1})	0.0	0.0	4.0	8.0	12.0	15.2	7.7	12.0	15.9	8.0	12.0	16.0
Secondary drain diameter (mm)	19.1	19.1	19.1	na	na	na	na	na	na	na	na	na
Flow rate at the secondary drain (L min^{-1})	12.0	12.0	11.7	na	na	na	na	na	na	na	na	na
Percent of total tank flow discharged through secondary/single drain as % of total tank outflow	100.0	100.0	74.6	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Surface loading rate discharged through secondary /single drain (L min^{-1}) flow per m^2 tank floor area	16.9	16.9	16.5	11.3	16.9	21.4	10.9	16.9	22.3	11.3	16.9	22.5

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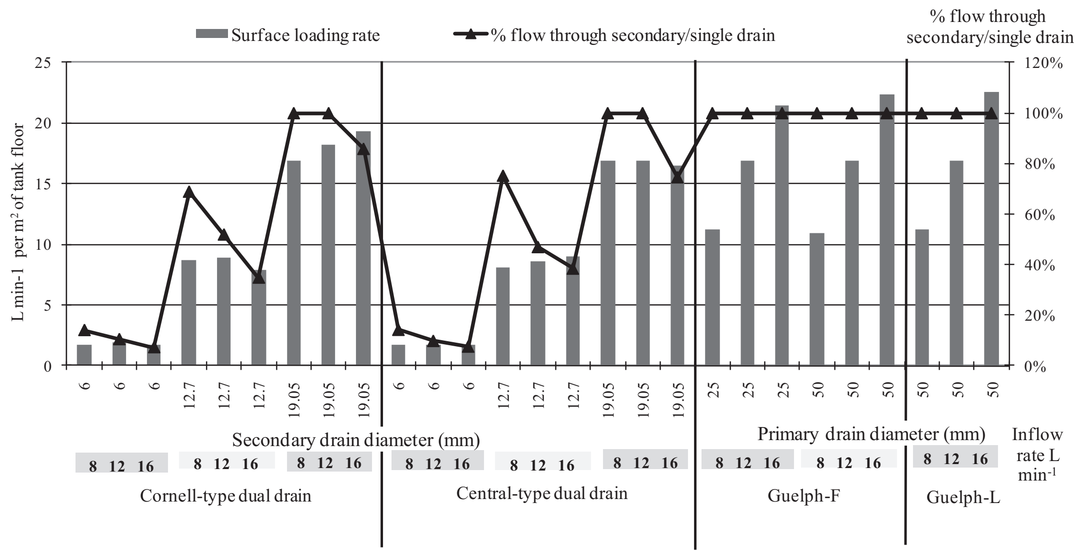

Fig. 4. Inflow rate, surface loading rate and flow discharged through bottom drain in the Cornell dual-drain, central dual-drain, Guelph-F and Guelph-L tanks for the determination of the digestibility with shrimp juveniles (results expressed as mean, $n = 3$).

A higher velocity in the inner perimeter is desirable to improve the solids flushing across the drain and into the settling devices. This criterion was fulfilled in the Guelph-F and Guelph-L systems with the 50 mm drain (inflow rate of 12 L min^{-1}), in the central-type dual-drain with the 12.7 mm secondary drain (inflow rate of 16 L min^{-1}) and 19.1 mm secondary drain (inflow rate of 12 L min^{-1}) (Fig. 5). In the central-type tank the tangential velocity near the center increased as the outflow increased due to the radial momentum carried by the flow of the swirling water moving down a path of decreasing radius.

In 10 and 150 m^3 tanks, the optimal water rotational velocities near the tank wall were reported to be 15–20 cm s^{-1} and 30–37 cm s^{-1}, respectively (Davidson and Summerfelt, 2004). In mixed cell raceways (MCR), mean water velocities of about 10.9–21.6 cm s^{-1} were reported (Labatut et al., 2007). The water velocity in the inner perimeter of the Guelph-L system (at the inflow rate of 16 L min^{-1}) was superior to the middle of the tank. Four replicates were done for this case. This behavior did not occurred with the other tank designs. This indicates that there may be some room for further improvement as to the water velocity profiles favoring higher velocities in the inner circumference with caution to avoid solids re-suspension and particles breakup.

In the Cornell-type dual-drain tank, the water velocity in the inner perimeter was equal to zero at inflow rates of 8 and 12 L min^{-1}, except in the 12 L min^{-1} and 19 mm secondary drain diameter set (Fig. 5). The Cornell-type dual-drain tank did not present a uniform water velocity profile and therefore it is not adequate for shrimp welfare nor solids removal. A short circuit between the water injected and the outflow through primary drain results in a non-uniform water velocity profile. Cornell-type dual-drain tanks seemed to be better suited for higher inflow rates and thus a smaller hydraulic exchange rate. Central-type dual-drain tanks might be a better option to concentrate solids in tanks with HET longer than 1 h (Davidson and Summerfelt, 2004).

At the inflow rate of 8 L min^{-1} most of the shrimp showed little activity and rested on the tank floor. The shrimp were able

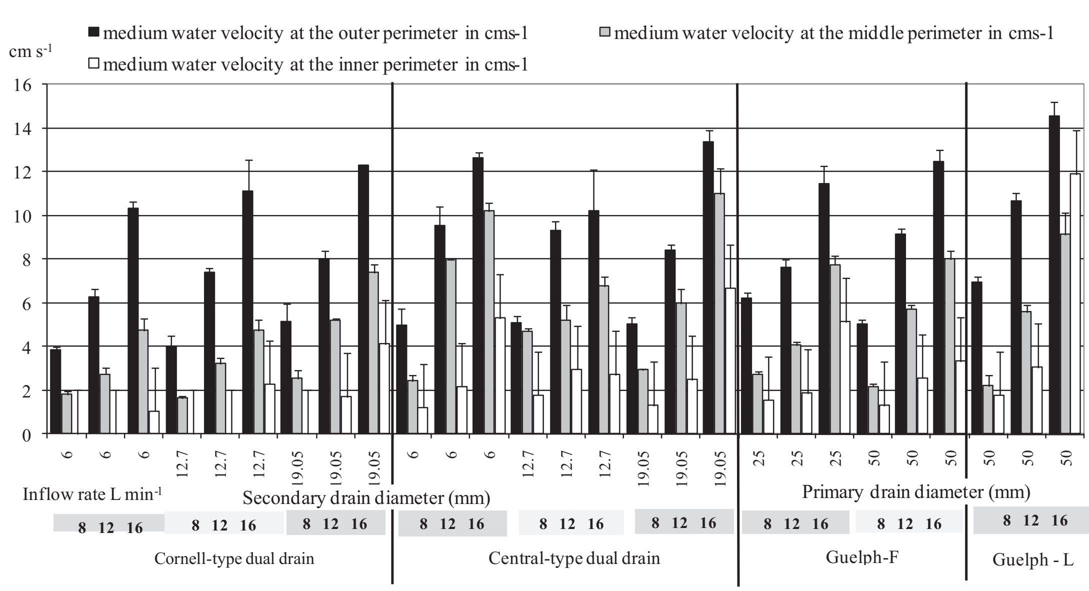

Fig. 5. Water velocity profiles in the inner, middle and outer perimeters according to the inflow rates and secondary or primary drain diameters in the Cornell dual-drain, central dual-drain, Guelph-F and Guelph-L tanks for the determination of the digestibility with shrimp juveniles (results expressed as mean, $n = 3$ and bars of standard error).

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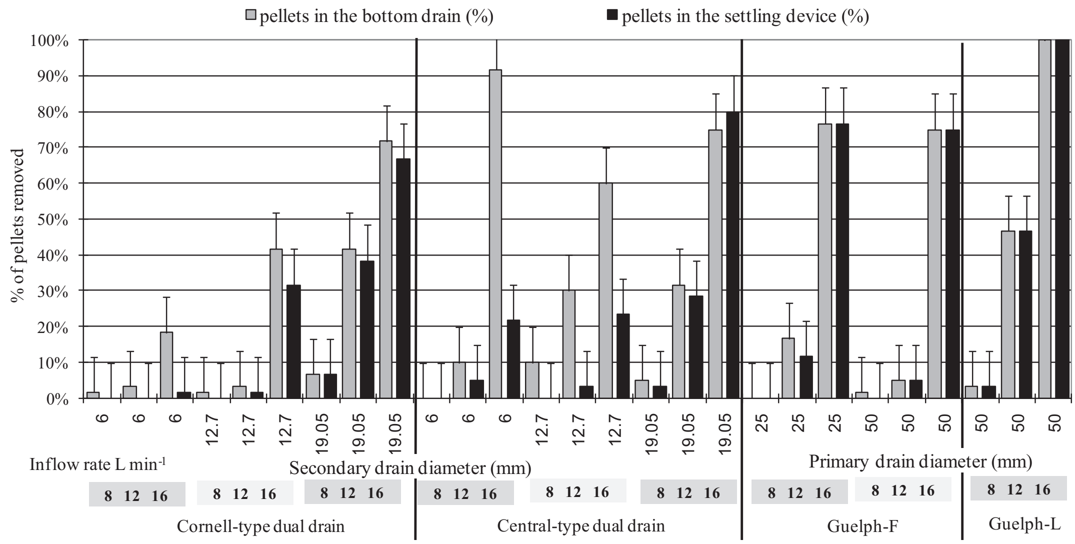

Fig. 6. Percentage of feed collected at the bottom drain and at the settling device in the Cornell-type dual-drain, central-type dual-drain, Guelph-F and Guelph-L tanks for the determination of the digestibility with shrimp juveniles (mean ± standard deviation, $n = 3$).

to capture feed particles and non-consumed feed and feces were reasonably removed by the current. As the inflow rate increased to 12 L min^{-1} the animals displayed active behavior and had difficulties in feeding. An improvement of the solids removal was noticeable. At the inflow rate of 16 L min^{-1}, most of the shrimp had to swim counter-current and failed to capture feed. Water velocities for shrimp nutritional studies should be based on capability of the tanks to rapidly flush feces and feed, enable proper shrimp behavior, avoid stressful conditions and energy expenditure. Promoting conditions for optimum growth and feed conversion rates should be considered.

3.3. *Solids flushing*

In the dual-drain tanks, the solids recovery efficiency was significantly affected by the inflow rate, the secondary drain diameter and the interaction of these two parameters ($P < 0.001$). In the single-drain tanks the solids recovery efficiency was significantly related to the system and inflow rate. An increase in the inflow rate was followed by an improvement on recovery efficiency ($P < 0.001$) (Fig. 6).

The highest inflow rates (12 and 16 L min^{-1}) corresponded to the highest solids recovery rate in all systems. The Guelph-L system at the highest inflow rates was the most efficient. At the inflow rate of 16 L min^{-1} 100% of the feed pellets were recovered in less than 3 min (Fig. 6). In the dual-drain tanks, the lowest inflow rate and smaller drain diameters resulted in a very low feed pellet recovery rate as pellets were trapped in the quiescent zone of the tank bottom. Higher inflow rates and larger drain diameters in the central type dual-drain tank and higher inflow rates in the Guelph tanks were more efficient to speedily flush the feed pellets (Fig. 6, Table 2).

The inlet flow rate influences the tangential velocity profile that in turn impacts the solids removal efficiency. The radial velocity of the water along the floor which is induced by the tea-cup effect is directly proportional to the tangential velocity. Since the radial velocity must be above a certain critical value to carry the solids along the floor, the tank becomes self-cleaning only when the tangential velocity is everywhere above a certain critical value.

In this study, tangential velocities above 6 cm s^{-1} (in the middle area of the tanks) seemed to improve the pellets removal efficiency. It possibly contributed to the fact that the Guelph-L system at the inflow rate of 12 L min^{-1} was the most balanced option for shrimp welfare and feed pellets flushing efficiency (47% recovery in 5 min or 1.9 pellets removed per minute) (Table 2).

The adaptation of the central-type dual-drain tank (12.7 mm secondary drain and an inflow rate of 12 L min^{-1}) with a 25 mm pipe branched into three vertical pipes that injected water at different depths increased the feed flushing speed and thus the percentage of feed pellets into the clarifier from 3% to 22% after 5 min. The advantages of a better orientation of water injection into the tank to improve its hydraulics for solids removal efficiency were well documented (Watten and Beck, 1987; Davidson and Summerfelt,

Table 2
Number of pellets recovered in the collector of the Cornell dual-drain, central dual-drain, Guelph-F and Guelph-L tanks according to drain diameters and inflow rates (means ± SD, $n = 3$) 5 min after the release of 20 shrimp feed pellets for the evaluation of tanks for shrimp digestibility determination.

System	Secondary or single drain diameter (mm)	Inflow rate (L min^{-1})		
		8	12	16
Cornell type	6	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	0.3 ± 0.6^{ab}
	12.7	0.0 ± 0.0^{a}	0.3 ± 0.6^{ab}	6.3 ± 3.5^{cd}
	19	1.3 ± 2.3^{ad}	7.7 ± 2.5^{c}	13.3 ± 3.8^{e}
Central type	6	0.0 ± 0.0^{a}	1.0 ± 1.7^{ac}	4.3 ± 0.6^{ac}
	12.7	0.0 ± 0.0^{a}	0.7 ± 1.2^{af}	4.7 ± 1.5^{ac}
	19	0.7 ± 1.2^{af}	5.7 ± 3.5^{bcdfg}	16.0 ± 3.0^{eh}
Guelph-F	25	0.0 ± 0.0^{a}	2.3 ± 2.1^{ac}	15.3 ± 1.5^{ei}
	50	0.0 ± 0.0^{a}	1.0 ± 1.7^{ac}	15.0 ± 2.0^{ei}
Guelph-L	50	0.7 ± 1.2^{a}	9.3 ± 1.2^{ceg}	20.0 ± 0.0^{hi}

Different letters indicate significant differences ($P < 0.05$).

2004; Oca and Masaló, 2007). Except for advanced RAS concepts it does not seems to be a common practice in aquaculture projects.

In comparison to clarifiers, the settling column performed better in the solids removal efficiency and also eliminated the horizontal flow and reduced the travel distance of the particles from the tank bottom to the sample flask at the collector, thus minimizing leaching. This feature is very important for solid matter recovery in digestibility studies.

The clarifiers seemed better suited for grow out or production purposes because of their relative simplicity, scale independency, easy cleaning and maintenance. In the last 4 years, the use of clarifiers has been adopted in shrimp super intensive culture systems with bioflocs and minimal water exchange to reduce the excess of suspended solids in microcosm tanks where the clarified water returned to the tank (Kumaraguru vasagam et al., 2009; Ray et al., 2010). A reduction of 59% of the SS was achieved in 6 m^3 tanks with settling chambers (Ray et al., 2010) and the use of this system is a promising tool for the concentration and use of bioflocs as a nutritive and inexpensive ingredient for shrimp feeds (Kuhn et al., 2009).

It took 5 and 6.25 min to remove all pellets in the Guelph-L systems and Cornell-type (with 19 mm secondary drain at 16 L min^{-1}), respectively. Yet the water velocity proved to be too fast for the shrimp wellbeing. In the Guelph-L system at the 12 L min^{-1} it took 10.8 min to remove all pellets, thus combining efficient pellets flushing and adequate water velocity profile (Table 2). These values are smaller than those reported in fish tanks where this task took between 1 and 6 min (Davidson and Summerfelt, 2004). The tank hydraulics had a direct impact on the water velocity profile which can be modified to increase the solids flushing through the mass displacement from the tank areas to the drain and then to the collector. Understanding the hydraulic features of the culture system is crucial when managing intensive systems specially when applied to practical farm conditions.

The main sources of waste in RAS are feces, biofloc and uneaten feed. Its removal has to be done as quickly as possible to avoid breakdown of the particles into smaller pieces, before they reach the settling devices, caused by shear stress created by aeration, turbulence and scrapping by the shrimp (Brinker and Rösch, 2005; Couturier et al., 2009). This sedimentation process depends on the inflow rate, specific gravity and size of the particles to be removed as well as the system design (Cripps and Bergheim, 2000; Johnson and Chen, 2006; Timmons et al., 1998). Other aspects to be considered are: stocking density, fish contact surface area, distance from water inlet, time of day, distance from the tank bottom, feed management and possibly feed composition (Brinker and Rösch, 2005).

A laboratory for shrimp nutrition studies with 36 Guelph-L digestibility tanks was constructed in the Instituto Oceanográfico da Universidade de Sao Paulo and the routine revealed that at inflow rates higher than 4 L min^{-1} was somewhat higher than the settling velocity of the shrimp feces carried with the water stream. At this flow rate a fine solids build up in the bottom drain increased the bottom drain wall roughness and particle accumulation. This problem was overcome by scrubbing the drain every other day. A second laboratory utilizing the same system is currently being constructed at the Universidade Federal do Rio Grande do Norte, in Brazil.

4. Conclusion

The water velocity and the pellets removal efficiency were influenced by system type in the dual-drain tanks but not in the single-drain tanks. The Guelph-L system presented the best performance among the systems evaluated as it combined a high pellets removal rate and a better water velocity profile and a shorter travel distance for the pellets to the sample flask.

Technologies involving hydrodynamic must be intensively applied to aquaculture to improve culture systems in terms of hydraulics, water velocity profile and solids removal for aquatic species production as well as research purposes like digestibility, which is highlighted in this study.

Disclosure statement

The authors declare that there is no conflict of interest including any financial, personal or other relationship with other people or organizations within 3 years of beginning the work that could inappropriately influence (bias) their work as this work was supported by official funding agencies of the Brazilian government and the other contributors provided comments and contacts.

Contributors

Rodrigo A.P.L.F. de Carvalho – participated in the design and conducted the research and article preparation.

Daniel E.L. Lemos – participated in the design of the research and article preparation.

Albert G.J. Tacon – participated in the design of the research and article preparation.

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References

Andoh, R.Y.G., Saul, A.J., 2003. The use of hydrodynamic vortex separators and screening systems to improve water quality. Water Science and Technology 47 (4), 175–183.

Barón, B.S., Bückle, L.F.R., Hernandéz, M.R., 2004. Intensive culture of *Litopenaeus vannamei* Boone 1931, in a recirculating seawater system. Ciencias Marinas 30 (1B), 179–188.

Brinker, A., Rösch, R., 2005. Factors determining the size of suspended solids in a flow-through fish farm. Aquacultural Engineering 33, 1–19.

Cho, C.Y., Slinger, S.J., 1979. Apparent digestibility measurement in feedstuffs for rainbow trout. In: Halver, J.E., Tiew, K. (Eds.), Finfish Nutrition and Fishfeed Technology, vol. II. Heinemann, Berlin, pp. 239–247.

Couturier, M., Trofimencoff, M., Buil, J.U., Conroy, J., 2009. Solids removal at a recirculating salmon-smolt farm. Aquacultural Engineering 41, 71–77.

Cripps, S.J., Bergheim, A., 2000. Review: Solids management and removal for intensive land-based aquaculture production systems. Aquacultural Engineering 22, 33–56.

Cruz-Suárez, L.E., Nieto-López, M., Guajardo-Barbosa, C., Tapia-Salazar, M., Scholz, U., Ricque-Marie, D., 2007. Replacement of fish meal with poultry by-product meal in practical diets for *Litopenaeus vannamei*, and digestibility of the tested ingredients and diets. Aquaculture 272, 466–476.

D'Abramo, L.R., Castell, J.D., 1997. Research methodology. In: D'Abramo, L.R., Conklin, D.E., Akiyama, D.M. (Eds.), Crustacean Nutrition, Advances in World Aquaculture, vol. 6. World Aquaculture Society, Baton Rouge, LA, pp. 3–25.

Davidson, J., Summerfelt, S.T., 2004. Solids flushing, mixing, and water velocity profiles within large (10 and 150 m^3) circular 'Cornell-type' dual-drain tanks. Aquacultural Engineering 32, 245–271.

Davidson, J., Summerfelt, S.T., 2005. Solids removal from a coldwater recirculating system – comparison of a swirl separator and a radial-flow settler. Aquaculture 33, 47–61.

Forster, I.P., Dominy, W., Obaldo, L., Tacon, A.G.J., 2003. Rendered meat and bone meals as ingredients of diets for shrimp *Litopenaeus vannamei* (Boone, 1931). Aquaculture 219, 655–670.

Freeman, D.W., Duerr, E.O., 1991. Design and use of outdoor microcosm laboratory tanks for the evaluation of shrimp diets. Aquacultural Engineering 10, 89–97.

Glencross, B.D., Smith, D.M., Thomas, M.R., Williams, K.C., 2002. The effects of dietary lipid amount and fatty-acid composition on the digestibility of lipids by the prawn, *Penaeus monodon*. Aquaculture 205, 157–169.

Glencross, B.D., Booth, M., Allan, G.L., 2007. A feed is only as good as its ingredients – a review of ingredient evaluation strategies for aquaculture feeds. Aquaculture Nutrition 13, 17–34.

Johnson, W., Chen, S., 2006. Performance evaluation of radial/vertical flow clarification applied to recirculation aquaculture systems. Aquacultural Engineering 34, 47–55.

Kuhn, D.D., Boardman, G.D., Lawrence, A.L., Marsh, L., Flick, G.J., 2009. Microbial floc meal as a replacement ingredient for fish meal and soybean protein in shrimp feed. Aquaculture 296, 51–57.

Kumaraguru vasagam, K.P., Suresh, A.V., Chamberlain, G.W., 2009. Growth performance of blue shrimp,Litopenaeus stylirostris in self-cleaning microcosm tanks. Aquaculture 290, 236–242.

Labatut, R.A., Ebeling, J.M., Bhaskaran, R., Timmons, M.B., 2007. Effects of inlet and outlet flow characteristics on mixed-cell raceway (MCR) hydrodynamics. Aquacultural Engineering 37, 158–170.

Lee, S.-M., 2002. Apparent digestibility coefficients of various feed ingredients for juvenile and grower rockfish (*Sebastes schlegeli*). Aquaculture 207, 79–95.

Oca, J., Masaló, I., 2007. Design criteria for rotating flow cells in rectangular aquaculture tanks. Aquacultural Engineering 36, 36–44.

Ray, A.J., Lewis, B.L., Browdy, C.L., Leffler, J.W., 2010. Suspended solids removal to improve shrimp (*Litopenaeus vannamei*) production and an evaluation of a plant-based feed in minimal-exchange, superintensive culture systems. Aquaculture 299, 89–98.

Smith, D.M., Tabrett, S.J., 2004. Accurate measurement of *in vivo* digestibility of shrimp feeds. Aquaculture 232, 563–580.

Smith, D.M., Tabrett, S.J., Glencross, B.D., Irvin, S.J., Barclay, M.C., 2007. Digestibility of lupin kernel meals in feeds for the black tiger shrimp, *Penaeus monodon*. Aquaculture 264, 353–362.

Summerfelt, S.T., Davidson, J., Timmons, M.B., 2000. Hydrodynamics in the 'Cornell-type' dual-drain tank. In: Libey, G.S., Timmons, M.B. (Eds.), The Third International Conference on Recirculating Aquaculture. 22 June–3 July, Virginia Polytechnic Institute and State University, Roanoke, VA, pp. 160–166.

Summerfelt, S.T., Sharrer, M., Marshall, C., Obaldo, L., 2006. Controlling water velocity within large Cornell-type dual-drain culture tanks. In: Sixth International Recirculating Aquaculture Conference, July 20–23, Roanoke, Virginia, pp. 382–393.

Tacon, A.G.J., 1996. Nutritional studies in crustaceans and the problems of applying research findings to practical farming systems. Aquaculture Nutrition 1, 165–174.

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

Timmons, M.B., Ebeling, J.M., 2007. Recirculating Aquaculture. Cayuga Aqua Ventures, Ithaca, NY, pp. 975.

Tseng, K.F., Su, H.M., Su, M.S., 1998. Culture of *Penaeus monodon* in a recirculating system. Aquacultural Engineering 17, 138–147.

Veerapen, J.P., Lowry, B.J., Colturier, M.F., 2005. Design methodology for the swirl separator. Aquacultural Engineering 33, 21–45.

Vinci, B.J., Summerfelt, S.T., Creaser, D.A., Gilletted, K., 2004. Design of partial water reuse systems at White River NFH for the production of Atlantic salmon smolt for restoration stocking. Aquacultural Engineering 32, 225–243.

Watten, B.J., Beck, L.T., 1987. Comparative hydraulics of a rectangular cross-flow rearing unit. Aquacultural Engineering 6, 127–140.

Zar, J.H., 2000. Biostatistical Analysis, 3rd ed. Prentice-Hall, New Jersey, pp. 659.

Zhang, P., Zhang, X., Li, J., Huang, G., 2006. Swimming ability and physiological response to swimming fatigue in whiteleg shrimp, *Litopenaeus vannamei*. Comparative Biochemistry and Physiology 145, 26–32.