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Review of circular tank technology and management

Michael B. Timmons [a,*], Steven T. Summerfelt [b], Brian J. Vinci [a]

[a] *Department of Agricultural and Biological Engineering, Cornell University, Ithaca, NY 14853, USA*
[b] *Conservation Fund Freshwater Institute, Shepherdstown, WV 25443, USA*

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Abstract

Large cost savings have been achieved in the production of food fish with the use of larger systems and enhanced production management strategies. These trends have also included the use of large circular culture tanks because of their many advantages for food fish production. Circular tanks make good culture vessels because they can provide a uniform culture environment, can be operated under a wide range of rotational velocities to optimize fish health and condition, and can be used to rapidly concentrate and remove settleable solids. The flow inlet and outlet structures and fish grading and/or removal mechanisms should be engineered to reduce the labor requirements of handling fish and to obtain effective tank rotational characteristics, mixing, and solids flushing. This paper reviews and discusses the rationale and criteria needed to design circular culture tanks. In addition, the implementation of continuous production and satiation feeding strategies within circular culture tanks is discussed because of their large and often under-emphasized effect on overall system productivity.

Keywords: Solids management; Tank geometry; Fluid mechanics; Hydraulics

1. Introduction

This paper reviews some of the current round culture tank design and management techniques being employed to lower system costs and achieve increased productivity. Possible mechanisms and the associated engineering criteria used to design water inlet and outlet flow structures, waste feed observation structures, and crowding and grading structures for large circular tanks will be described. Discussion is limited to tank systems, but can be generally applied to either flow-through designs or water recirculating systems.

* Corresponding author. Tel.: +1 607 2552801 fax: +1 607 2554080; e-mail: mbt3@cornell.edu

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2. Culture tank engineering

Cost savings have been achieved in the production of food fish with the use of large tank based systems and enhanced production management strategies. Substantial savings in both capital and labor costs can also be realized by shifting production into fewer but larger culture tanks. Our experience has been that the labor needed to care for a tank is somewhat independent of the tank size, i.e. it takes the same amount of time to analyze water quality, distribute feed, and perform cleaning chores for 1 m^3 or 100 m^3 tanks. Also, capital costs of tanks per unit volume greatly decrease as size is increased. These advantages must be balanced against difficulties that could arise within large culture tanks, such as:

- distributing flow to obtain uniform mixing and rapid solids removal;
- grading and harvesting fish;
- removing mortalities;
- isolating the biofilter while treating the fish with a chemotherapeutant;
- risk of larger economic loss per tank failure due to mechanical or biological reasons.

Of particular concern is the risk of failure because tanks typically fail as units. The more fish in a tank, the bigger the economic loss that will occur when a tank fails. However, as the experience of the management and design team increases, the risk of tank failure decreases, but should never be ignored.

Large tanks are more critically dependent upon tank hydraulic design than small tanks, because in small tanks, ≤ 1 m^3, the overall rate of water exchange tends to be rapid. The rapid hydraulic exchange results in reasonably good water quality, because the high turnover rate carries more oxygen into the tank and rapidly flushes wastes. Conversely, in large tanks, the hydraulic retention time tends to be lower and, as a result, the inlet and outlet injection methods and flow rate become dominant factors affecting the uniformity of water conditions in the tank (aside from the feed loading rate). The carrying capacity of a tank is influenced by water exchange, feeding rate, oxygen consumption, and waste production (Losordo and Westers, 1994).

Tanks used for intensive fish culture are of varied shape and flow pattern (Wheaton, 1977; Piper et al., 1982; Klapsis and Burley, 1984; Cripps and Poxton, 1992). Tanks are designed with considerations for production cost, space utilization, water quality maintenance, and fish management. There is a definite trend towards large circular culture tanks for food fish production. Tanks > 10 m in diameter, which used to be referred to as pools, are now reasonable choices for culture systems in intensive indoor operations. Circular tanks are attractive for the following reasons:

- simple to maintain;
- provide uniform water quality;
- allow operating over a wide range of rotational velocities to optimize fish health/condition;
- settleable solids can be rapidly flushed through the center drain;

- permit designs that allow for visual or automatic observation of waste feed to enable satiation feeding.

The water inlet and outlet structures and fish grading and/or removal mechanisms should be engineered to reduce the labor requirement for fish handling and to obtain uniform water quality, rotational velocities, and solids removal within the circular tank.

The self-cleaning ability is a key advantage of circular tanks. Recommended tank diameter to depth ratios vary from 5:1 to 10:1 (Burrows and Chenoweth, 1955; Chenoweth et al., 1973; Larmoyeux et al., 1973); even so, many farms use tanks with diameter:depth ratios as low as 3:1 and circular silo tanks use diameter:depth ratios on the order of 1:3. Recent studies from the SINTEF Norwegian Hydrotechnical Laboratory (Skybakmoen, 1989; Tvinnereim and Skybakmoen, 1989) indicate that the flow injection mechanism can be designed to minimize tank hydraulic problems. Selection of a tank diameter:depth ratio is also influenced by factors such as the cost of floor space, water head, fish stocking density, fish species and fish feeding levels and methods. Choices of depth should also consider ease of workers handling fish within the tank and safety issues of working in waters that may be more than 'chest' high.

Circular tanks can approach relatively complete mixing, i.e. the concentration of a dissolved constituent in the water flowing into the tank changes instantaneously to the concentration that exists throughout the tank. Therefore, if adequate mixing can be achieved, all fish within the tank are exposed to the same water quality. Good water quality can be maintained throughout the circular culture tank by optimizing the design of the water inlet structure and by selecting a water exchange rate so that the limiting water quality parameter does not decrease production when the system reaches carrying capacity.

The rotational velocity in the culture tank should be as uniform as possible from the tank wall to the center and from the surface to the bottom, and it should be swift enough to make the tank self-cleaning. However, it should not be faster than that required to exercise the fish. Water velocities of 0.5–2.0 times fish body length s^{-1} are optimal for maintaining fish health, muscle tone, and respiration (Losordo and Westers, 1994). Velocities required to drive settleable solids to the tank's center drain should be greater than 15–30 cm s^{-1} (Burrows and Chenoweth, 1970; Mäkinen et al., 1988). For tilapia, Balarin and Haller (1982) reported an upper current speed of 20–30 cm s^{-1}. For salmonids, Timmons and Youngs (1991) provided the following equation to predict safe non-fatiguing water velocities:

$$V_{\text{safe}} < 5.25/(L)^{0.37} \tag{1}$$

where V_{safe} is the maximum design velocity (about 50% of the critical swimming speed) in fish lengths s^{-1} and where L is the fish body length in cm. In circular tanks, velocities are reduced somewhat away from the walls, which allows fish to select a variety of water velocities, as compared to raceway designs where velocities are uniform along the channel.

3. Circular tank inlet flow structures

Circular tanks are operated by injecting water flow tangentially to the tank wall at the tank outer radius so that the water spins around the tank center, creating a primary rotating flow. However, as several have summarized (Burrows and Chenoweth, 1955; Larmoyeux et al., 1973; Wheaton, 1977; Skybakmoen, 1989; Tvinnereim and Skybakmoen, 1989; Paul et al., 1991; Goldsmith and Wang, 1993), the no-slip condition that exists between the primary flow and the tank's bottom and side walls creates a secondary flow that has an appreciable inward radial flow component at the tank bottom and an outward radial flow at the tank surface (Fig. 1). This inward radial flow along the bottom of the tank carries settleable solids to the center drain and can create the self-cleaning property so desired in circular tanks. Unfortunately, in a circular tank with such flow, a torus-shaped region about the center drain can become an irrotational zone with lower velocities and poor mixing (Fig. 1). The magnitude of the irrotational zone depends on the introduction of tangential flows near the walls, the diameter:depth ratio, and the overall rate of flow leaving the center bottom drain. Because the irrotational zone has lower water velocities and does not mix well, it can decrease the effective use of the culture tank by producing short circuiting of flow, by creating localized water quality gradients (especially of concern are reduced oxygen levels), and by providing a quiescent zone where solids can settle and collect.

The self-cleaning attribute of the circular tank is in part related to the overall rate of flow leaving the center bottom drain. Further, solids removal also depends upon the fish re-suspending the settled materials. This explains in part why tanks with low fish biomass do not clean as well as tanks with higher biomass. In addition, because aquaculture solids have specific gravities that are relatively close to water (typically 1.05–1.2 versus 1.0; Chen et al., 1993; Potter, 1997), sloping the floor

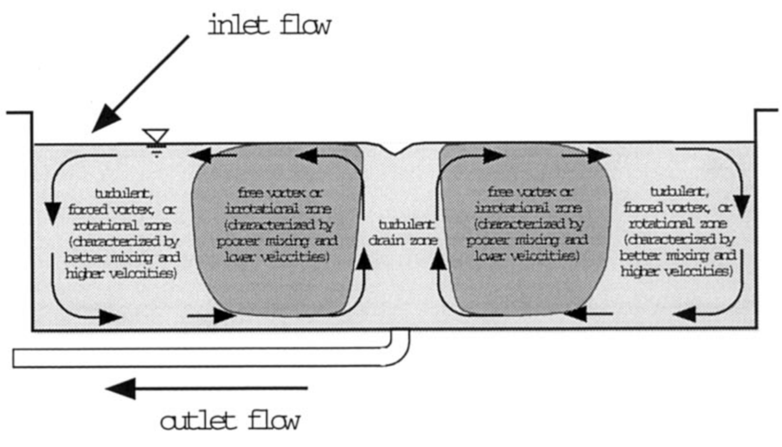

Fig. 1. The 'primary' rotating flow (not shown, but created by injecting the flow tangential to the tank wall) creates a 'secondary' rotation that flows radially (shown here) and carries settleable solids towards the tank's bottom center drain in a phenomenon called the 'tea-cup effect'.

towards the center drain does not improve the self-cleaning attributes of a circular tank. Sloped floors are often only useful when a circular tank is drained for maintenance purposes.

Rotational velocity can be controlled by design of the water inlet structures, so water flow does not have to be increased beyond that required for the fish's culture environment (Klapsis and Burley, 1984; Skybakmoen, 1989; Tvinnereim and Skybakmoen, 1989). Tvinnereim and Skybakmoen (1989) reported that the current velocity in a tank can be largely controlled by varying the inlet impulse force (F_i), which is defined as:

$$F_i = \rho \cdot Q \cdot (v_{orif} - v_{rota}) \tag{2}$$

where ρ is the density of water (kg m^{-3}), Q is the inlet flowrate (m^3 s^{-1}), v_{orif} is the velocity through the openings in the water inlet structure (orifices or slots) (m s^{-1}), and v_{rota} is the rotational velocity in the tank (m s^{-1}). The inlet impulse energy largely dissipates as it creates turbulence and rotation in the rotational zone (Fig. 1). The impulse force, and thus the rotational velocity in the tank, can be regulated by adjusting either the inlet flow rate or the size and/or number of inlet openings (Tvinnereim and Skybakmoen, 1989). Paul et al. (1991) reported that the tank rotational velocity is roughly proportional to the velocity through the openings in the water inlet structure, especially near the tank wall, i.e.

$$v_{rota} \approx \alpha \cdot v_{orif} \tag{3}$$

where the proportionality constant (α) is generally from 0.15–0.20 (personal communication, A. Skybakmoen, AGA AB, Lidingö, Sweden), depending on the design of the inlet flow structure. The manner of flow injection influences: (i) the uniformity of the velocity profile through the tank, (ii) the strength of the secondary radial flow along the tank bottom towards the center drain (i.e. the ability of the tank to move settleable solids to the center drain), and (iii) the uniformity of water mixing. Skybakmoen (1989) and Tvinnereim and Skybakmoen (1989) compared the tank hydraulics that resulted from injecting the water flow tangentially at the outer radius of the circular tank with either:

- a traditional open-ended pipe point source;
- a short, horizontal, submerged, distribution pipe with its axis oriented towards the tank center and with evenly spaced openings along its length (directed at 30¡ below the water surface);
- a vertical submerged distribution pipe with evenly spaced openings along its length;
- an inlet flow distribution pipe that combines both vertical and horizontal branches (Fig. 2).

Skybakmoen (1989) and Tvinnereim and Skybakmoen (1989) reported that the open-ended pipe created: (i) non-uniform velocity profiles in the tank (e.g. much higher velocity profiles the tank wall), (i) poor mixing in the irrotational zone that resulted in short circuiting of the flow, (iii) resuspension of solids to all tank depths, and (iv) poor flushing of solids from the bottom. With respect to the horizontal submerged pipe inlet, they reported that water exchange and water mixing was

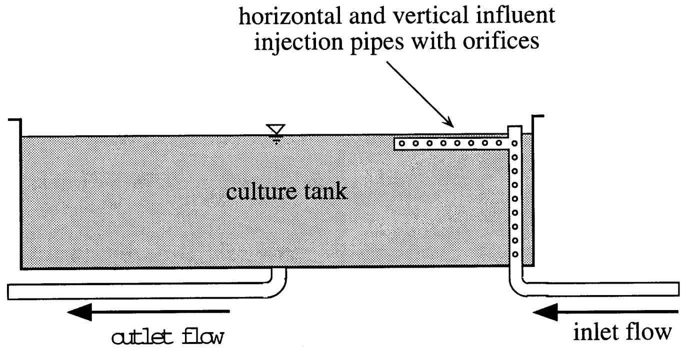

Fig. 2. Water injected into culture tanks through evenly spaced openings (holes or slots) in both horizontal and vertical injection pipes produces more uniform rotational velocities both radially and vertically, more uniform mixing, and better solids flushing.

effective throughout the tank, but that a weaker and less stable bottom current (for solids cleaning) resulted. Regarding the vertical submerged inlet distribution pipe, they reported that it provided better self-cleaning than when injecting the water flow through an open-ended pipe or a horizontal distribution pipe, but that the strong bottom current (responsible for particle removal) also resulted in poor mixing in the irrotational zone and short circuiting and therefore less efficient use of the flow exchange. They reported that an inlet flow distribution pipe that combines both vertical and horizontal branches (Fig. 2), when placed somewhat away from the wall so that fish can swim between the pipe and wall, was an effective way to: (i) achieve uniform mixing, (ii) prevent short circuiting of flow, (iii) produce uniform velocities along both the tank's depth and radius, and (iv) effectively transported waste solids to the tank bottom and out the center drain.

For large circular or square tanks, e.g. diameter >6 m, placing multiple flow distribution pipes at different tank locations can improve solids removal, velocity uniformity, and water quality homogeneity (Klapsis and Burley, 1985). However, inlet distribution pipes can interfere with fish handling. This problem can be solved by incorporating the flow distribution orifices within the tank wall, as is the case in cross-flow culture tanks (Watten and Johnson, 1990). Unfortunately, economic considerations may preclude these more 'elegant' solutions. Additionally, these distribution orifices and nozzles would have to be shaped to inject the flow parallel to the tank wall and might not provide as uniform a flow distribution as that produced by placing the injection pipes away from the wall. The system should be designed so that pipes can be removed during harvest or, alternatively, harvest methods should be developed that work around the pipes.

4. Circular tank outlet flow structures

Circular fish culture tanks concentrate settleable solids, e.g. fecal matter, feed fines, and uneaten feed, at their bottom and center. The tank center is then the continuously withdraw settleable solids through a center standpipe that also controls water depth requires use of two concentric pipes. Perforated slots at the base of the outer pipe (Larmoyeux et al., 1973) or a gap at the base of the outer pipe (Surber, 1933) forces flow to be pulled from the bottom of the tank (capturing settleable solids) and the inner pipe is used as a weir to set the water depth within the tank (Fig. 3). Surber (1933, 1936) developed the self-cleaning center standpipe (Fig. 3) and recommended creating an adjustable gap between the bottom of the outer pipe and the tank bottom in order to increase suction while forcing the flow to leave at the tank bottom where settleable solids collect. The distance between the two pipes, i.e. the annular space should be selected to create a velocity large enough (0.3–1.0 m s^{-1} depending upon the size and density of the particles) to entrain solids up to the top of the inner pipe. Wheaton (1977) reported that using a center standpipe within large circular tanks with strong radial flows can cause upward vertical flow around the center standpipe, which can carry settleable solids upward with the flow. Wheaton (1977) felt that this problem could be eliminated by the use of bottom outlets and external standpipes.

When water depth is controlled by an external standpipe, a vertical perforated plate or screen (Fig. 4) can be used to cover the bottom center drain; this allows solids to leave the tank but excludes fish (Piper et al., 1982; Skybakmoen, 1989; Tvinnereim and Skybakmoen, 1989). Another patented method uses an annular approach plate to enhance particle entrapment (Fig. 5, Lunde et al. (1997)). Likewise, a horizontal pipe with an annular space created by a gap between its base and the floor (similar to the pipe configuration reported by Surber (1933, 1936)) has been used to assist solids removal from a culture tank where water depth was controlled with an external standpipe (Josse et al., 1989).

Corrosion-resistant screening material, such as perforated sheets of aluminum, stainless steel, fiberglass, or plastic are used to cover drain outlets (Piper et al., 1982; Sedgwick, 1985). Piper et al. (1982) and Pankratz (1995) recommended perforated screening with horizontal oblong slots instead of holes, because the slots are easier to clean, provide greater open area, and do not clog as readily as round holes. Piper et al. (1982) recommended specific slot sizes depending upon the size of fish (Table 1). Ideally, openings through the screen covering the center drain should be small enough to exclude fish and yet large enough not to become clogged with feed pellets or fecal matter. Entrapment of fish on the outlet occurs when fish cannot escape the area in front of the drain because the water velocity in that area is too great. Fish impingement is minimized by providing a total open area through the outlet screen so that the water velocity through the screen is ≤ 30 cm s^{-1}. Depending upon the species and life stage, certain situations particularly with smaller fish require water velocities ≤ 15 cm s^{-1} (Pankratz, 1995), e.g. see Eq. (1). These velocities do not produce a significant pressure drop through the screen openings, thus minimizing fish impingement.

Not all aquatic species require screening to prevent their escape down the bottom center drain. Tanks (4.9–9.1 m diameter tanks) have been used to culture salmonid

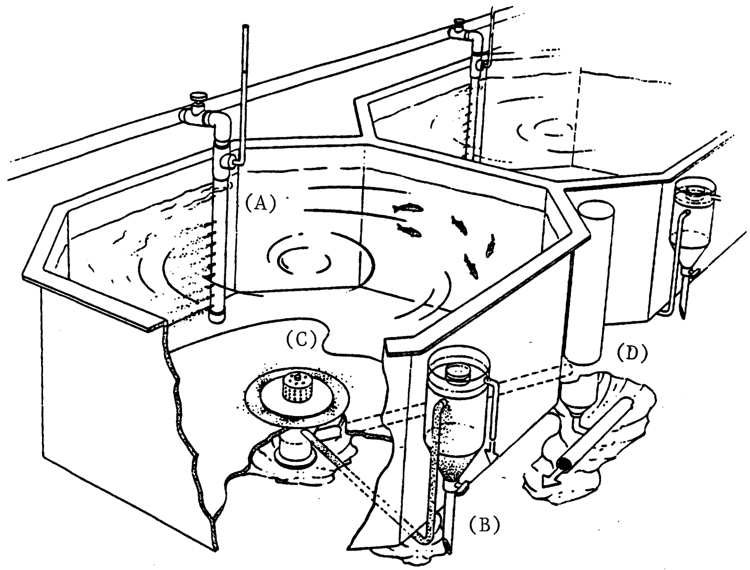

Fig. 5. A solid annular approach plate fixed above the bottom center drain was developed and patented by Lunde et al. (1997) to exclude fish and enhance particle removal by accelerating particles into the drain. This illustration of an AquaOptima AS culture unit also shows a water injection mechanism (A), an external swirl separator attached to the bottom drain (B), a second drain (just above the bottom center drain) for withdrawing water relatively low in solids (C), and an external standpipe assembly (D) (reproduced by permission of AquaOptima AS).

species with no fish exclusion screening over their center drain (S. Wilton, P.R.A. Manufacturing, Nanaimo, BC, personal communication). This design links the unscreened bottom drain to an external standpipe chamber, which contains a weir to control water depth, a screen to capture dead fish, and a drain (Fig. 6). According to Wilton (personal communication) fish escapement down the uncovered center drain was not reported as a problem, because salmonids do not tend to swim down that kind of current. Depending upon the regulatory authority, more stringent escape preventing methods may be required.

Table 1
The horizontal oblong slot size depends upon the size of fish to be retained

Slot size (mm)	Fish size (g)
1.6 × 3.2	Fry–0.45
3.2 × 6.4	0.45–2.3
6.4 × 12.7	2.3–15
12.7 × 19.1	≥15

Fish species was not specified, from Piper et al. (1982).

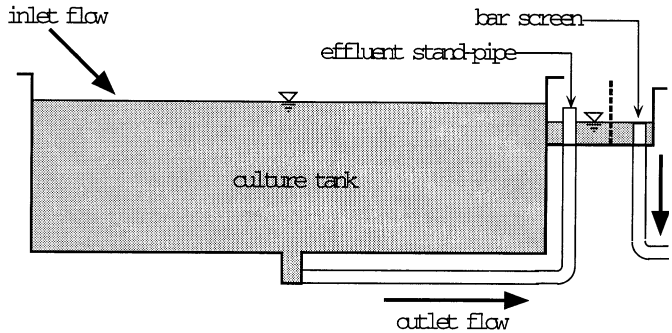

Fig. 6. An unscreened bottom drain linked to an external standpipe chamber, which contains a weir to control culture tank depth and a bar screen to capture dead fish. This culture tank system can be modified to provide a second drain on the upper-portion of the tank side wall, which allows the tanks to be operated as swirl separators (S. Wilton, personal communication; used by permission of P.R.A. Manufacturing).

5. Dual-drain structures for concentrating solids

Circular fish culture tanks can be managed as 'swirl settlers', settling basins with two effluents, because of their capability to concentrate solids at their bottom and center. Solids that concentrate at the bottom center can be removed in a small flow stream by using a bottom-drawing center drain, while the majority of flow is withdrawn at an elevated drain. Cobb and Titcomb (1930) and Surber (1936) were the first to report the use of a second bottom-drawing drain to remove solids that were settled in the center of circular culture tanks. MacVane (1979) and Slone et al. (1981) also report use of a bottom-drawing drain to remove settleable solids, while the bulk of the water overflowed the top of deep circular tanks (depth:diameter ratio of 3:1), sometimes called silo culture tanks. These early reports laid out the basic approach for use of the dual-drain system.

More recently, settled solids have been reportedly concentrated in 5–20% of the total flow that leaves the bottom center drain of circular culture tanks when the remainder of the flow leaving the tank (roughly 80–95% of the total) was withdrawn through a fish-excluding port located above the bottom-drawing drain (Mäkinen et al., 1988; Eikebrokk and Ulgenes, 1993; Lunde et al., 1997) or part-way up the tank's side wall (Fig. 7) (Timmons, 1997). Additionally, Lunde et al. (1997) developed and patented a solid annular approach plate fixed above the bottom center drain that can be incorporated into a center dual-drain system (Fig. 5). In addition, a dual-drain design (Fig. 8) was patented by Van Toever (1997).

The dual-drain approach has large economic implications, because solids removal costs in aquaculture are controlled more by the volume of flow that is treated rather than the solids concentration of the effluent that is treated. Therefore, to reduce treatment cost, space requirements, and headloss requirement of solids removal

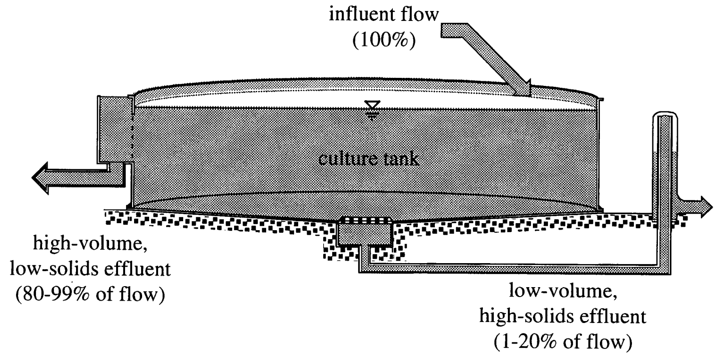

Fig. 7. A circular culture tank with a bottom center drain and an elevated drain part-way up the tank's sidewall (Timmons, 1997).

units, circular culture tanks have been designed with dual effluent structures in order to concentrate the majority of settleable solids in only a fraction of the total tank flow (5–20% of the total), which is carried out through the tank's bottom center drain. The lower flow rate from the effluent pipe may also provide a more effective means to apply ozone to a system to further enhance solids removal (Summerfelt et al., 1997).

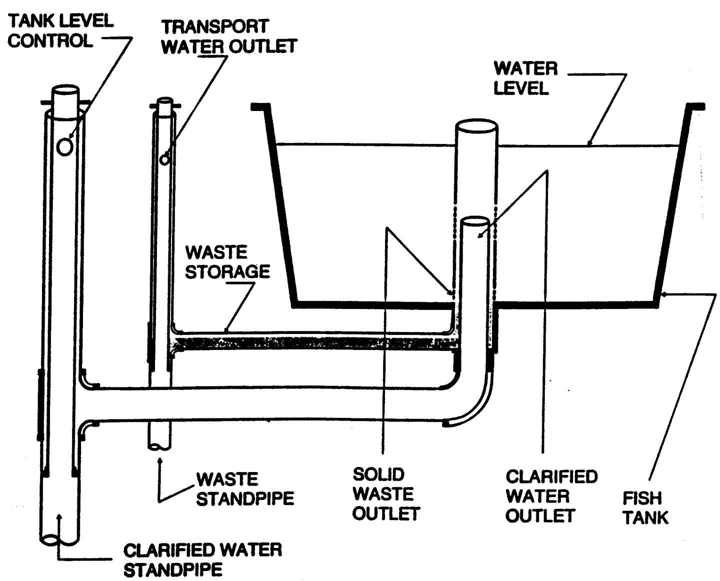

Fig. 8. A dual-drain design patented by Van Toever (1997) and marketed through Waterline. (used by permission of Waterline).

6. Solids balance

The effectiveness of the dual-drain tank at concentrating solids within the bottom center drain discharge can be illustrated by a steady state solids balance written over the culture tank,

$$\{\text{TSS carried in influent}\} + \{\text{TSS produced feeding}\}$$
$$= \{\text{TSS leavingsidewall outlet}\} + \{\text{TSS leaving centers drain}\} \tag{4}$$

or more explicitly,

$$\{Q \cdot \text{TSS}_{\text{in}}\} + \{P_{\text{TSS}}\} = \{Q_{\text{out1}} \cdot \text{TSS}_{\text{out1}}\} + \{Q_{\text{out2}} \cdot \text{TSS}_{\text{out2}}\} \tag{5}$$

where Q is the flow rate into the tank (m^3 day^{-1}), Q_{out1} is the flow rate leaving the sidewall drain (m^3 day^{-1}), Q_{out2} is the flow rate leaving the bottom center drain (m^3 day^{-1}), TSS_{in} is the TSS concentration into the tank (kg m^{-3}), TSS_{out1} is the TSS concentration leaving the sidewall drain (kg m^{-3}), TSS_{out2} is the TSS concentration leaving the bottom center drain (kg m^{-3}), and P_{TSS} is the TSS production rate (kg TSS produced day^{-1}).

P_{TSS} is determined by using the following equation:

$$P_{\text{TSS}} = a_{\text{TSS}} \cdot r_{\text{feed}} \cdot \rho_{\text{fish}} \cdot V_{\text{tank}} \tag{6}$$

where ρ_{fish} is the density of fish in the culture tank (kg fish m^{-3} culture volume), V_{tank} is the volume of water contained within culture unit (m^3 culture volume), r_{feed} is the feeding rate (kg feed kg fish^{-1} day^{-1}), and a_{TSS} is the TSS produced as a proportion of feed fed (kg TSS kg feed^{-1}).

The fraction of solids removed (f_{rem}) through the tank center drain can be determined from the following equation:

$$f_{\text{rem}} = \frac{Q_{\text{out2}} \cdot \text{TSS}_{\text{out2}}}{(Q_{\text{out1}} \cdot \text{TSS}_{\text{out1}}) + (Q_{\text{out2}} \cdot \text{TSS}_{\text{out2}})} \tag{7}$$

Eq. (7) can be rearranged, substituted into Eq. (5), and then rearranged again to allow for TSS_{out2} to be calculated from f_{rem}, Q, Q_{out2}, P_{TSS}, and TSS_{in}:

$$\text{TSS}_{\text{out2}} = \{(Q \cdot \text{TSS}_{\text{in}}) + P_{\text{TSS}}\} \cdot \frac{f_{\text{rem}}}{Q_{\text{out2}}} \tag{8}$$

Use of the double drain approach, greatly increases the concentration of solids being removed from the low flow bottom center drain. The concentration of solids in this low flow may be as much as 10 times or more higher than the concentration of solids that leave the main flow drain, whether it is located in the tank sidewall or as an upper center drain. In a dual-drain tank system used for tilapia culture, Timmons (1997) employed 100% solids removal through the center bottom drain (2–3% of the total flow for the system). In this same study, the concentration of solids in the side-wall drain (same as overall tank suspended solids) were 6.4 mg l^{-1} (S.D. of 3.6). In this study, daily feeding rates were approximately 80 kg day^{-1}, the tank volume was 53 m^3, the center bottom drain flow was 110 l min^{-1}, and the

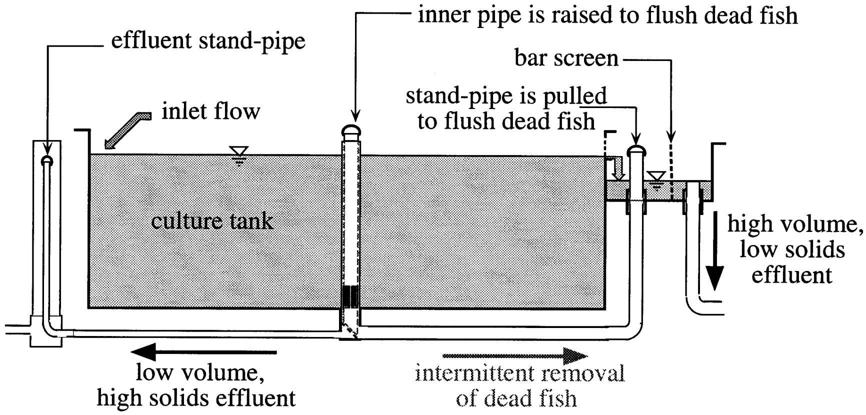

Fig. 9. A concentric pipe system to flush solids and remove dead fish from the bottom center drain; also shown is an elevated drain for removing the high volume, low solids effluent.

total water flow to the biofilters and water conditioning units was 3.6–5.5 m^3 min^{-1}. All net settleable solids were removed through the center bottom drain and captured either by a mechanical screen filter and/or a settling tank (emptied daily, approximately 3 m^3).

7. Fish management in culture tanks

7.1. Mechanisms to remove dead fish

Daily removal of dead fish from the bottom center drain is important. Dead fish in the fish culture system can influence: (i) profits, (ii) fish health, (iii) water quality, (iv) solids removal, and (v) the water level in the tank. Commercial fish farmers want a simple and reliable way to remove daily mortalities with minimal labor. There are a variety of approaches to address this need. When applicable, an uncovered bottom center drain (Fig. 5) makes the task of removing dead fish easy. When dead fish sink, they are carried in the radial flow to the bottom center drain where they are sucked through to the external standpipe chamber.

Methods to remove dead fish and/or waste solids from the bottoms of deep culture environments have been developed for large floating cages (Braaten, 1991; Skjervold, 1993), which when enclosed in bags rather than nets (Solaas et al., 1993) look very similar to circular culture tanks. These mortality and solids removal methods look transferable to land-based circular culture tanks.

A dead fish collector can be incorporated into the dual-drain particle trap mechanism, (Fig. 5). The illustration does not detail how fish are removed through the particle trap, but dead fish are flushed through the larger drain pipe to the external standpipe structure where they are removed.

Another method for removing dead fish incorporates the center drain outlet screen into the inner pipe of a two-pipe center post system (Fig. 9). The outer pipe consists of a steel post secured in the tank floor such that large openings cut into the pipe just above the tank floor level allow dead fish to pass through the outer pipe when the inner pipe is lifted (Fig. 9). The sizes of the outer and inner concentric pipes have been selected to make a close but unhindered fit. To conveniently flush dead fish captured at the bottom center drain, the inner pipe is raised inside the fixed center post while the external standpipe over the mortality drain is removed; this produces a surge of flow that carries the dead fish out of the tank (Fig. 9). The effectiveness of this mortality removing mechanism is still under review.

The culture tank shown in Fig. 9 can be operated with one or two discharges. It can be operated as a swirl separator when flow is discharged both over the weir (on the right-hand-side of Fig. 9) and also through the bottom drain (towards the standpipe on the left hand side of Fig. 9). Conversely, the culture tank shown in Fig. 9 can be operated with a single effluent when all the flow goes down the main center drain (towards the standpipe on the right-hand-side of Fig. 9). In either operating mode, dead fish can be flushed periodically through the main center drain (towards the standpipe on the right-hand-side of Fig. 9). Caution should be exercised when manipulating flows, particularly where diversion or temporary flow cessation may also compromise the supply of oxygen to the fish tank.

7.2. Feed management and waste feed observation structures

The method and rate of feeding can have a very large and often under-emphasized effect on overall system production (Hankins et al., 1995). One method that is used to increase total system production is to feed higher quality diets (Storebakken and Austreng, 1987; Seymour and Bergheim, 1991; Mayer and McLean, 1995; Thorpe and Cho, 1995) and/or to improve feed consumption by using satiation feeding methods (Summerfelt et al., 1995). The type of feed and feeding technique are critical for successful production, because they influence feed conversion and growth rate, as well as the amount of feed wasted. Improved feed utilization can lead to improved growth and better production economics. Feeding fish to satiation with a high quality feed is particularly important for maximizing growth. Also, wasted feed can be very costly and it increases the cost of water quality treatment.

Being able to observe whether the fish have been fed to or near satiation is critical in order to maximize productivity. Such monitoring can be accomplished by designing the bottom center drain so that the effluent leaves the culture tanks through a standpipe structure that allows workers to see uneaten feed or allows automatic detection of waste feed. Our experience has been to select a pipe diameter to maintain pipe velocities from 0.3 to 1.0 m s^{-1} to ensure that waste feed flushes rapidly once it enters the effluent drain piping, especially for vertical piping.

Waste feed can be manually observed at the effluent outlet structure that leaves the bottom center drain of circular culture tanks. Uneaten feed can be manually observed in a swirl separator receiving the majority of solids from the culture tank (Fig. 5). In all of these methods, uneaten feed must be distinguished from normal feces so that the feed rate can be adjusted. If the feed is delivered slowly (over the course of approximately 0.5–1.0 h) fish will feed to satiation, and feeding can be terminated after small quantities of uneaten feed are observed in order to minimize waste feed.

Another method for feeding to satiation uses an automatic control device that uses ultrasound to detect uneaten feed and controls the duration or intensity of feeding based upon the quantity of waste feed detected. This technology was originally developed to control feeding within sea cage systems used to culture salmon (Juell, 1991; Blyth et al., 1993; Juell et al., 1993). An ultrasonic waste feed control device has been developed for circular culture tanks (Durant et al., 1995; Summerfelt et al., 1995; Derrow et al., 1996). The device uses an ultrasonic probe in the tank effluent standpipe to detect uneaten feed and then turns off the feeder after a pre-determined quantity of waste feed has been detected. The device can detect uneaten feed and yet filter out the weaker signals resulting from feces.

7.3. Culture tank crowding and grading structures

The total system production can be increased by using a continuous production strategy, rather than a batch production strategy (Watten, 1992; Summerfelt et al., 1993; Heinen et al., 1996). The advantage of continuous stocking and harvesting is that the production system stays closer to its carrying capacity, so feeding rates are maintained near maximum on a continuous basis leading to maximum economic productivity. These methods have been implemented successfully in both trout (Heinen et al., 1996) and tilapia culture (Timmons, 1997).

Continuous stocking and harvesting strategies require frequent fish handling, which may be difficult and/or stressful to the fish (depending upon species and handling method). Additionally, when cohorts are mixed within a culture unit and market size fish are harvested at frequent intervals, the manager can lose track of the feed conversion rate. Ultimately, in continuous stocking, the farmer will obtain overall feed conversion and growth statistics, but there can be as much as a year lag in this information. This would be much less of a problem for a mature facility and expert management than for less experienced managers.

Effectively implementing a continuous stock management strategy, depends largely on the methods used to handle fish and the design of the culture tank. A convenient mechanism that can be used to grade fish and harvest each culture tank can be incorporated into the culture tank design. The obvious method is to simply net the fish out of the tank, or to use a net to crowd the fish for harvest or grading. Fish can be lifted out of the tank with a pump, net, or cage once crowded. Another crowding/grading method uses crowder/grader gates that pivot around the culture tank center post to separate different size groups (Larmoyeux et al., 1973; Piper et al., 1982). On a large farm, the grader gates could contain removable panels with evenly spaced rods so that fish could be selectively harvested at different sizes by changing the grader panels. The grader gates would have to be lifted out of the tank when they were not in use. Under some tank flow situations, a crowder might also be installed and left in place for several hours or a day to allow self sorting. By sectioning off an area of the tank with two crowding dividers, swimming and feeding behavior could be used to implement self sorting.

Considering the importance of grading and harvesting fish from circular tanks, there is minimal information published on this subject. No matter what methods are implemented, incorporating harvesting and grading mechanisms into the culture facility is one of the most important aspects of culture tank design because of its high impact on the overall costs of production.

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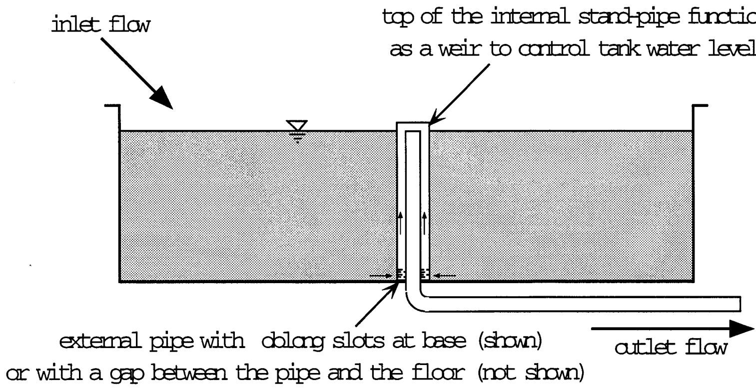

Fig. 3. An internal standpipe made of two pipes can be used to both control depth and to remove solids from the tank bottom. The outer pipe is used to pull flow from the bottom of the tank and the inner pipe is used to set the water depth within the tank.

logical location for the bottom drain. The bottom center drain should be designed to continuously remove the concentrated settleable solids and for the intermittent removal of dead fish that are captured at the bottom center drain (discussed more fully in a later section). The bottom center drain structure is also used for water level control by connecting it to a weir, either on the inside (Fig. 3) or the outside of the tank (Fig. 4).

When a center standpipe is used on the inside of a tank, it can be designed so that it either captures and stores settleable solids near the drain (where they can be flushed at intervals, Surber (1936), Klapsis and Burley (1985)), or it continuously withdraws settleable solids from the bottom of the culture tank (Surber, 1936; Burrows and Chenoweth, 1955; Larmoyeux et al., 1973; Josse et al., 1989). To

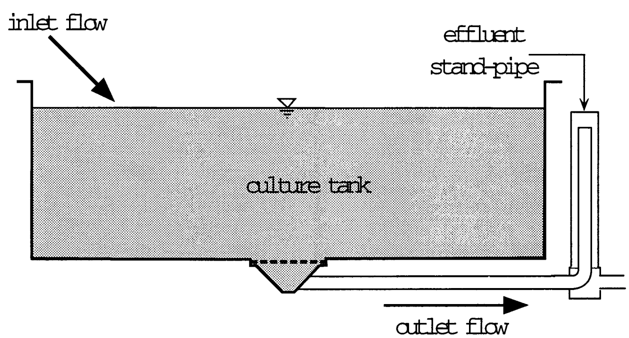

Fig. 4. Excluding fish from the center drain with a vertical perforated plate or screen requires the use of an external standpipe to control water depth, but makes the standpipe easily accessible and avoids obstructions in the center of the tank.