Hydrodynamics in the 'Cornell-Type' Dual-Drain Tank

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Introduction

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center can be removed in a small flow stream by using a bottom-drawing center drain, while the majority of flow is withdrawn at an elevated drain. The two drains have been typically located at the tank's center, which then takes advantage of both the 'tea-cup effect' and the strength of the overall flow when it drains through the tank center, as reviewed by Timmons et al. (1998). However, the 'Cornell-type' dual-drain culture tank differs significantly from the other dual-drain designs, because it only places the bottom drain at the tank's center and removes the majority of flow through an elevated drain located on the tank's side-wall. This paper reports an investigation of water mixing and settleable solids fractionation within a 'Cornell-type' double-drain circular culture tank.

Materials and Methods

Settleable solids fractionation and tank mixing were studied within a 3.66 m (12 ft) i.d. x 1.22 m (4 ft) tall circular 'Cornell-type' dual-drain tank at the Freshwater Institute. Replicated tests were conducted under two hydraulic exchange rates (1 and 2 rearing tank volume exchanges per hour), at three diameter to depth ratios (12:1, 6:1, 3:1), three bottom drain flow percentages (5, 10, and 20% of total flow), and in the presence and absence of rainbow trout. Some of the trials could not be conducted, however, because the flow rates through the tank's bottom drain were too low to flush pellets through the 3.8 cm (1.5 in) diameter drainpipe. Trout were maintained at densities exceeding 60 kg/m^3 and fish were fed 1% body weight per day. The experimental protocol and the methods described were in compliance with the Animal Welfare Act (9CFR) requirements and were approved by the Freshwater Institute's Institutional Animal Care and Use Committee.

Bottom drain flows were set and calibrated using a calibrated bucket and a stop watch. Total flow was measured using a pipe-mounted flow meter; these flows were checked using a stop watch and a larger basin of known volume. Total suspended solids (TSS) concentrations were measured during all trials where fish were present. TSS samples were collected on the tank's inlet flow, both tank outlet flows, and the tank's bottom-center drain outlet flow after it has passed through a microscreen filter.

Tank Mixing Tests

Rhodamine WT dye was added to the culture tank in a single pulse to determine the effectiveness of tank mixing under the different conditions tested. Dye-pulse flushing was monitored by collecting water samples over a period of time (Figure 1).

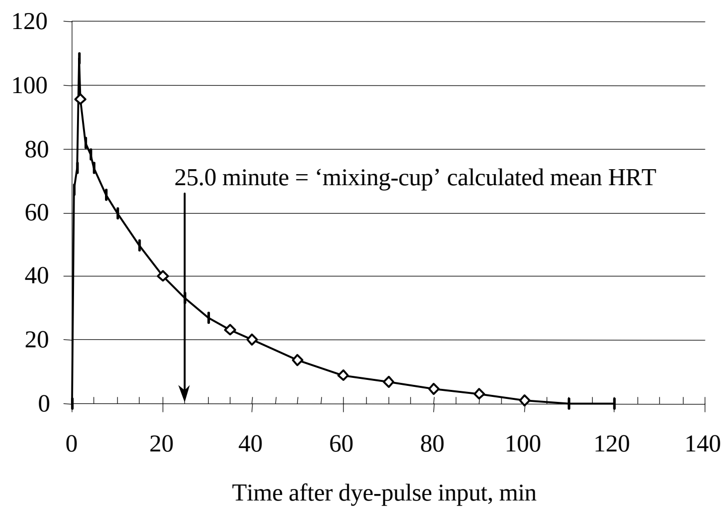

Figure 1. An example plot showing the absorbance data for each sample taken after the dye-pulse was added to the culture tank.

The mean hydraulic retention time (HRT) of the water flowing through the culture tank was estimated using the "mixing-cup" method described on page 63.3 of Levenspiel (1989), as follows:

$$\text{measured mean residence time (min)} = \frac{\sum_{i=1}^{n} t_i \cdot C_i \cdot \Delta t_i}{\sum_{i=1}^{n} C_i \cdot \Delta t_i} \qquad \text{(Eq. 1)}$$

where: C_i is the absorbance of sample i, t_i is the length of time the sample i was collected after the dye-tracer was input into the tank, and Δt_i is the interval between adjacent samples when sample i was collected. The 'mixing-cup' method accounts for unequal sample intervals within the data.

The ideal mean residence time was also calculated by dividing the water volume in the tank (V) by the water flowrate through the tank (Q). Tank turnover efficiencies were estimated from the ratio of the two residence times found above:

$$\text{turnover efficiency} = \frac{\text{measured mean residence time (min)}}{\text{ideal mean residence time (min)}} \qquad \text{(Eq. 2)}$$

If mixing within the tank is perfect, the tank turnover efficiencies equal 1.0. Turnover efficiencies of less than 1.0 indicate less than perfect mixing and that some water short circuits through the culture tank. Turnover efficiencies greater than 1.0 are an indication of problems with the precision of water flow rate or tank volume measurements, or inconsistencies within the samples taken during the dye-tracer test.

Pellet Flushing Tests

Pulses of sinking PVC cylindrical pellets (each about 3 mm in length by 3 mm o.d.) were added to quantify solids flushing kinetics and the relative strength of the radial flow. The plastic pellets had a specific gravity of 1.05, similar to the specific gravity reported for trout fecal matter. The plastic pellets also exhibited a settling velocity of 3.8 cm/s, which was similar to the settling velocity reported for fecal matter 1.7-4.3 cm/s (Warrer-Hansen, 1982). Feed pellets tested in this study settled more rapidly (e.g., 14 cm/s) than the plastic pellets, but the feed pellet settling velocities measured were similar to those reported by others.

During a pellet flushing test, 1000-grams of dry pellets were weighed out, wetted in a bucket to remove air bubbles from the pellets, and placed into the tank water in a pulse. The plastic pellets settled fairly rapidly and were transported by radial flow towards the bottom-center drain. The plastic pellets were then collected from the discharge from the bottom-center drain at specific time intervals. Baskets containing 1-mm mesh stainless steel screen were used to capture the pellets from the flow during each sampling interval. Another screened basket was placed to capture all pellets flushed through the side-wall drain. Following collection, the pellets were oven dried and then weighed. Minimums of three pulsed-pellet tests were run for each set of conditions.

An unsteady-state mass balance was developed to quantify pellet flushing, assuming zero pellet inflow, reaction, or accumulation, i.e., Loss = ~~Inflow~~ – Outflow – ~~Reaction~~ – ~~Accumulation~~. The outflow term in the mass balance was broken into a component representing simple mass action of flow to the bottom drain, and a component representing pellet enrichment at the bottom drain due to a combination of sedimentation and radial flow (assuming that the pellet outflow at the tank's sidewall is negligible); this was done to distinguish between the two different mechanisms transporting pellets to the bottom center drain, i.e., Loss =– Outflow (mass action) – Outflow (enrichment). Or more specifically,

$$V \cdot \frac{dC}{dt} = -Q_{out,b} \cdot C_{out,b} - k \cdot C_{out,b} \cdot V$$
$$= V \cdot \left\{-\left(Q/V + k\right) \cdot C_{out,b}\right\} \quad \text{(Eq. 3)}$$

Where: k is a 1st order rate constant characterizing bead enrichment at the bottom-center drain and $Q_{out,b}$ and $C_{out,b}$ are the flowrate and concentration of pellets flushed through the bottom center drain at a given time. Integration provides an equation that can be used to model pellet flushing through the bottom drain in real time:

$$C_{out,b}(@\,t) = C_{out,b}(@\,t = 0) \cdot e^{\{-(Q/V+k) \cdot t\}} \quad \text{(Eq. 4)}$$

Note that the flushing of a homogeneously distributed dye pulse is only due to mass action and would result in a similar equation, but without k (1st order enrichment constant). Therefore, the k-value increases the rate of solids flushing relative to the culture tank exchange rate. After manipulation of Eq. 4, the k-value for each pellet flushing test was calculated from the slope of the line produced by plotting the pellet flushing data (Figure 2) after manipulation to the following form:

y-axis = -LN(fraction of solids remaining) (Eq. 5)
x-axis = t (Eq. 6)
slope of the linear regression line = (Q/V + k) (Eq. 7)

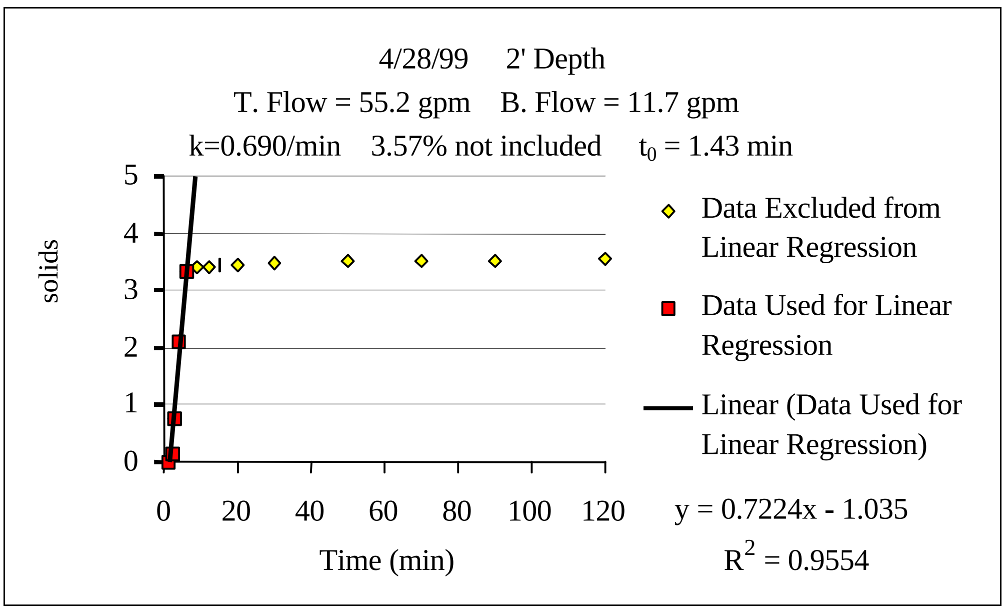

Figure 2. An example plot showing pellet-flushing data plotted as the natural logarithm of the 'fraction of pellets remaining' for each outlet sample taken after a pulse of pellets was added to the culture tank. The data not included in the linear regression only represented 3.57% of the total mass of pellets flushed from the tank.

A sample pellet-flushing test is shown in Figure 2. Note that not all the data fits the assumption that pellet enrichment at the bottom center drain due to settling and radial flow could be approximated by 1^{st} order kinetics. In most tests, effective pellet flushing occurred and only a small portion (e.g. less than 15%) of the pellets did not flush according to the 1^{st} order kinetic equation.

Results and Discussion

Solids Partitioning Between Side-wall and Bottom-Center Drains

Less than 5% of the sinking pellets were flushed through the side-wall drain during all trials. However, larger fractions of pellets were flushed through the side-wall drain when fish were present (e.g., < 4.3%) than during trials conducted in the absence of fish (e.g., < 1.4%). Increasing the culture tank exchange rate from 1 ex/hr to 2 ex/hr also increased the fraction of pellets flushed through the sidewall drain.

The k-values estimated from the pellet-tracer tests are an indication of the rate that pellets can be flushed from the bottom-center drain and also of the relative strength of the radial flow. When fish were present, the rate that pellets were flushed through the bottom-center drain was greater at 2 ex/hr than at 1 ex/hr and at the smaller diameter:depth ratios. All the trials at 2 ex/hr and diameter:depth ratios of 3.1:1 and 6:1 produced strong radial flows, rapid solids flushing, and exhibited no problems with solids flushing.

A very important observation was that the settleable solids frequently deposited about the tank's bottom-center drain during most trials at 1 ex/hr, but only at the diameter:depth ratio of 12:1 during trials at 2 ex/hr. During these trials, the radial flow transported the settleable solids to the center portion of the tank, but water velocities were so low in the middle of the tank that a good portion of these solids settled within a torus-shaped region about the center drain. Fortunately, this accumulation of settled solids were usually sufficiently near to the center drain that pulling the external stand-pipe regulating the bottom-center drain flow, even for an interval of < 1 min, was sufficient to flush the accumulated solids. The presence of fish improved the rate that pellets were flushed through the bottom-center drain (i.e., the K-values in Table 1) for a given diameter:depth, underflow percentage, and overall tank exchange rate.

The relative importance of the two pellet flushing mechanisms, i.e., mass action (i.e., Q/V) versus enrichment at bottom-center drain (k), was illustrated by calculating the percentage of pellet flushing due to enrichment alone:

$$\%\,\text{flushing due to enrichment} = \frac{k}{k + Q/V} \cdot 100 \qquad \text{(Eq. 8)}$$

The radial flow mechanism played a much larger role than the mass transport mechanism in the transport of pellets to the bottom-center drain during the trials at 2 ex/hr and diameter:depth ratios of 3.1:1 and 6:1 and during the 1 ex/hr trials at diameter:depth ratios of 3.1:1 (Table 1). Pellets were not flushed effectively during the remainder of the trials, so the k-values and the enrichment percentage shown in Table 1 could not be calculated under these conditions.

Table 1. The relative amount of flushing produced by enrichment (i.e., k/[k+Q/V]*100) at the bottom-center drain was calculated for each trial that a k-value (listed before enrichment-value) could be estimated.

	k-value ± standard error (min) / enrichment ± standard error (%)		
	Dia:depth = 3.1:1	Dia:depth = 6:1	Dia:depth = 12:1
2 ex/hr (fish present)			
5% bottom flow	0.39±0.02 / 93±0	0.13±0.05 / 71±14	NA
10% bottom flow	0.48±0.01 / 94±0	0.34±0.05 / 91±2	0.02±0.02 / 58±14
20% bottom flow	0.87±0.24 / 96±1	0.58±0.06 / 95±1	0.07±0.03 / 0
1 ex/hr (fish present)			
5% bottom flow	0.06±0.04 / 84±2	NA	NA
10% bottom flow	0.06±0.03 / 62±24	0.08±0.04 / 65±17	NA
20% bottom flow	0.10±0.04 / 80±7	0.20±0.02 / 91±1	NA
2 ex/hr (no fish)			
5% bottom flow	0.08±0.04 / 61±17	NA	NA
10% bottom flow	0.53±0.14 / 93±2	NA	NA
20% bottom flow	1.37±0.02 / 98±0	0.00±0.01 / 12±12	NA
1 ex/hr (no fish)			
5% bottom flow	-0.01±0.00 / 83±0	NA	NA
10% bottom flow	0.01±0.04 / 29±9	NA	NA
20% bottom flow	0.08±0.00 / 0	NA	NA

Note, an enrichment-value of zero indicates that the term (k/[k+Q/V]*100) was negative, e.g., the beads took longer to flush than the hydraulic exchange rate through the tank. NA indicates that either bead flushing was so poor that k-values could not be calculated, or that bottom-drain pipe velocity was too low to flush beads and the tests were not run.

Additionally, not all of the data was included in the linear regression of the bead-pulse data as plotted according to the –LN(fraction of solids remaining) versus time, as in the example shown in Figure 2. This data was excluded because it did not fit the 1st order kinetics assumption for solids enrichment at the bottom-center drain. We think that when large portions of the pellets did not exhibit enrichment at the center drain according to 1st order kinetics, it was due to insufficient velocity in the rotational flow, i.e. the actual water velocity starting from the outside wall. Under these low velocity conditions, the pellets did not flush rapidly because they settled on the tank floor just before reaching the tank's center drain. Velocities at the outside walls appear to require velocities of at least 15 cm/s (0.5 ft/s) to promote solids departure from the center drain.

The pellet-pulse data when plotted according to the –LN(fraction of solids remaining) versus time (Figure 2) also provides a graphical estimate of the time required for the beads to travel from the tank's surface to the bottom center drain, i.e., the dead time (t_0) for solids flushing from the tank. The x-intercept of this data provides the estimate of the tank's dead time. When fish were present, average dead times ranged from 1.0 to 2.6 min for all conditions tested.

Tank Mixing

When water rotates about a circular tank, a torus-shaped region about the center drain can become an irrotational zone with lower velocities and poor mixing (Timmons et al., 1998). However, according to the dye-tracer tests, the 'Cornell-type' dual-drain tank exhibited good mixing characteristics during all trials with fish present, as illustrated by tank turnover efficiencies near 1.0. However, mixing was often better during the 2 ex/hr trials than at the 1 ex/hr trials.

Settleable Solids Fractionation and Waste Management

Due to variability in the TSS data, the TSS data collected during all trials was combined according to its sampling location. This data indicates that the flow discharged from the 'Cornell-type' tank's bottom-center drain contained TSS concentrations (i.e., 19.6 ± 3.6 mg/L) that were more than 10-times greater than the TSS concentration discharged from the side wall drain (i.e., 1.5 ± 0.2 mg/L). For these trials, the concentration of TSS discharged from the side-wall drain was sufficiently low that it would not require further solids treatment in order to pass even many of the more stringent discharge limits imposed by environmental regulatory agencies. On the other hand, the concentrated and relatively small flow discharged from the bottom-center drain would definitely require treatment before discharge. However, this flow was treated effectively using a microscreen filter where, on average, capture of the TSS discharged from the circular culture tank's bottom-center drain was greater than 80%.

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