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# Do fish enhance tank mixing?

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**Abstract**

The design of fish rearing tanks represents a critical stage in the development of optimal aquaculture systems, especially in the context of recirculating systems. Poor hydrodynamics can compromise water quality, waste management and the physiology and behaviour of fish, and thence, production potential and operational profitability. The hydrodynamic performance of tanks, therefore, represents an important parameter during the tank design process. Because there are significant complexities in combining the rigid principles of hydrodynamics with the stochastic behaviour of fish, however, most data upon tank hydrokinetics has been derived using tanks void of fish. Clearly, the presence of randomly moving objects, such as fish, in a water column will influence not only tank volumes by displacing water, but due to their activity, water dynamics and associated in-tank processes.

In order to determine the impact of fish presence upon tank hydrodynamics, Rhodamine fluorometry was employed to examine mixing within a recirculating aquaculture system. Two different methods were compared, traditional, outlet-based measurements and a technique that employed in-tank data acquisition. Circular tanks were employed during data collection either in the presence or absence of experimental fish-red drum *Sciaenops ocellatus* ($n=36$; 5 kg total wet wt); and at two flow rates. Irrespective of flow rate, the presence of fish dramatically enhanced the mixing process ($P<0.001$), with mixing times in tanks with fish being one-third that for tanks without animals. In-tank dispersion coefficients and dispersion numbers also differed ($P<0.001$) in the presence of fish, irrespective of flow. Presence or absence of fish had no effect upon hydraulic residence or circulation times. Unlike measurements at the outlet, in-tank observations were more able to isolate the effects of stochastic, fish-induced mixing, from deterministic, hydrodynamic mixing.


*Keywords:* Hydrodynamics; Tracer; Hydraulic residence time; Rhodamine; Dispersion number; Red drum

## 1. Introduction

Recirculating aquaculture systems (RAS) present the aquaculturist with several advantages. Principal in

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this regard is the ability to tailor production conditions (water chemistry, photoperiod, etc.) to optimize the performance characteristics of the cultured species (Skjolstrup et al., 2000). Enhanced control over production enables greater harvest flexibility that in turn permits more precise market management which may increase returns on investment. Additionally, because of their reduced consumption of water and heightened management of wastes, RAS provide environmentally acceptable production systems (Wheaton, 2002; Rasmussen et al., 2004). Moreover, water reuse techniques can reduce energy and labor costs, provide flexibility in the placement of hatcheries and offer a high level of biosecurity from pollution, predator, disease and human viewpoints (Skjølstrup et al., 1998). The major drawback of recirculating aquaculture relates to their overall complexity and the large capital costs required for facility start-up. Generally, the latter is offset by increasing stocking densities. Such strategies, however, are intrinsically dangerous since crowding may negatively impact product quality and feed efficiency, while occurrence of and losses due to disease intensify (Wagner et al., 1997; Shoemaker et al., 2000).

Holding tanks are the central feature of RAS. Tanks may be circular, oval, raceway, D-ended, octagonal, hexagonal, square, conical, or hybrids thereof, in form. A wide variety of materials are used in tank construction including fiberglass, plastic, concrete, wood, steel and their amalgams. Increasingly, RAS employ barrier-based earthen ponds, especially in shrimp production. Selection of construction material for tanks is generally constrained by size, desired shape and site characteristics. For example, costs severely limit the use of steel whereas large tank size restricts application of plastics and fiberglass. The use of concrete and earthen ponds may be impeded to a certain degree by site topography, hydraulic permeability, soil plasticity and prevailing height of water tables. Irrespective of size or construction material employed, however, to achieve maximum production potential, a prerequisite to RAS, tanks must be optimally designed. A complete appreciation of tank hydrodynamics represents a vital part of the engineering process since this characteristic may impair water quality (Burrows and Chenoweth, 1955; Burley and Klapsis, 1988). Poor water quality reduces stocking potential, decreases growth, negatively affects feed conversion, influences tank microbiology and elevates stress and consequently the likelihood of losses due to disease. Poorly regulated tank mixing can result in changes in physiology, more pronounced aggression (Griffiths and Armstrong, 2000; Odeh et al., 2003) and the formation of social hierarchies, a reduction in sedimentation and solid waste removal and increased occurrence of dead volumes (Cripps and Bergheim, 2000; Rasmussen et al., 2004).

Several studies have examined general mixing processes in aquaculture ponds and tanks (Burrows and Chenoweth, 1955, 1970; Larmoyeux et al., 1973; Burley and Klapsis, 1988; Gaikowski et al., 2004; Rasmussen and McLean, 2004). However, because it is extremely complex to integrate the more rigid principles of hydrodynamics with the stochastic behaviour of fish, most research in this field has employed fishless tanks. In studies that have examined the effect of fish upon tank mixing processes, results have generally been contradictory or inconclusive (Burley and Klapsis, 1985; Watten and Beck, 1987; Watten et al., 2000), most likely due to the experimental and/or analytical procedures employed. Traditionally, mixing studies estimate dispersion numbers using tracer techniques. The principal method employed involves inspection of dye dilution using single-point measurements taken at the tank outlet. However, this technique does not provide critical detail upon in-tank hydrodynamic processes and difficulties are encountered in assessing the impact of fish upon the mixing process with any degree of certainty. Due to the importance of this field of investigation (Burley and Klapsis, 1985; Watten and Beck, 1987; Watten et al., 2000), there remains a clear need to intensify research upon the effect of fish presence on tank hydraulics. An increased awareness of these effects would assist in refining the tank design process.

One method of enhancing the current understanding of tank hydrodynamic processes might be to undertake in-tank measurements of dye dilution. In contrast to outlet-based methods, in-tank techniques permit multiple determinations to be made per experiment. Moreover, because in-tank measurements may provide a more accurate evaluation of changes in hydrodynamics over time, the effects of fish presence upon mixing processes might be more readily

assessed. The objective of the present study was to compare outlet-based and in-tank methods for examining the mixing process, both in the absence and presence of fish, and at high and low flow rates. Circular tanks were used in preference to any other form because these units are the most common encountered in commercial settings while also permitting acquisition of multiple measurements following single tracer injection.

## 2. Materials and methods

### 2.1. System configuration

All studies were undertaken using a four-tank seawater recirculating aquaculture system. This system had been in continuous operation for a period of 2 years for the holding of red drum, cobia and summer and southern flounders. Throughout this period, no mortalities were recorded in any of the tanks. The recirculation configuration (Fig. 1) comprised a KMT-based (Kaldnes Miljøteknologi, Tønsberg, Norway) fluidized bed biofilter for conversion of ammonia to nitrate, a bead filter (Aquaculture Technologies Inc., Metaire, LA, USA) used to eliminate solids (uneaten feed, fecal material, mucus and other fish waste), a protein skimmer for removal of dissolved material and a UV sterilizer (Aquatic Ecosystems, Apopka, FL, USA) for disinfections. The fluidized bed was oxygenated using diffusion air lines connected to a 1-hp Sweetwater remote drive regenerative blower (Aquatic Ecosystems, Apopka, FL, USA). Water temperature and $DO_2$ were monitored daily using an Y85 Series dissolved oxygen meter (YSI Inc., Yellow Springs, OH). Total ammonia nitrogen (TAN) was monitored daily by spectrophotometric analysis (Hach Inc., Loveland, CO, USA). Nitrite and nitrate levels were quantified once weekly. Lighting was derived from banks of commercial phosphorescent tubes positioned 6 m above the experimental system. Salinity was measured with a temperature-compensated refractometer (Aquafauna Bio-Marine, Hawthorne, CA, USA).

Tank 1 (Fig. 1) was used as the experimental tank whereas tanks 2 and 4 were employed to hold experimental animals. To maintain a constant flow into tank 1, water was pumped from tank 3 using a submersible pump (Little Giant Pump, Oklahoma City, OK, USA). This strategy was used in order to avoid changes in flow due to the accumulation of organic matter within the bead filter. Water flow into tank 1 was carefully monitored using a Dialog MM3 flowmeter (Master Meter, Mansfield, TX, USA). Flow rates into tank were controlled using valve adjustments to the feeder line from tank 3. Maximum flow rates of 0.5 l $s^{-1}$ were attainable using this arrangement. Water temperature was maintained at 22 °C and

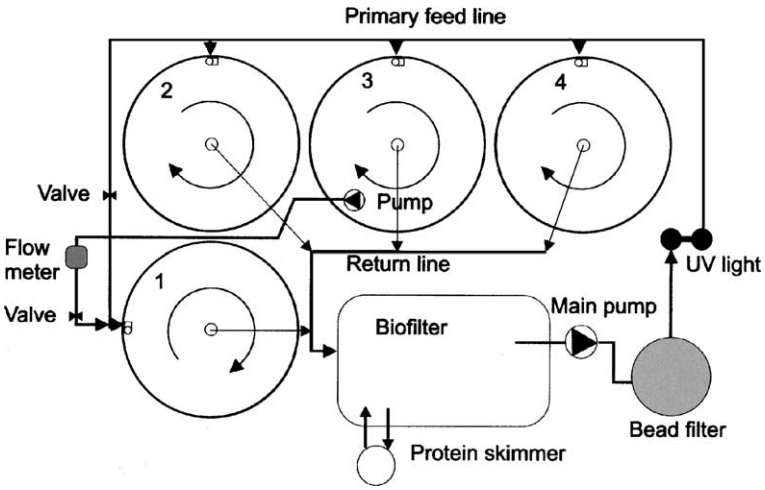


Fig. 1. Principal design and configuration of the experimental marine recirculating aquaculture system employed during the current investigations.

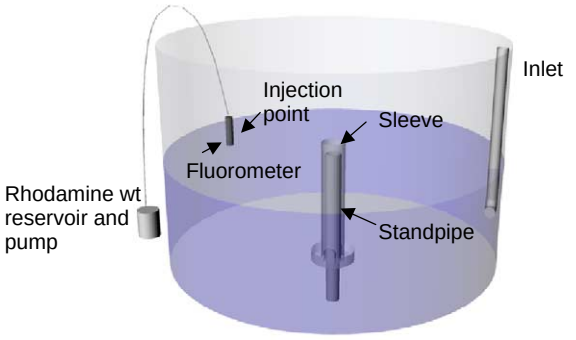


Fig. 2. Diagram illustrating the overall component arrangement of the experimental tank used during the present studies.

salinity of 8‰. Throughout experimental measurements, oxygen concentrations were maintained at ≥7 mg $l^{-1}$.

Tank mixing was measured using Rhodamine WT (Aquatic Ecosystems, Apopka, FL, USA). This tracer was selected due to its low toxicity and sorption properties. Fluorescence was measured using a Cyclops 7 Submersible Flourometer (Turner Designs, Sunnyvale, CA, USA).

Experiments were performed using two configurations (Figs. 2 and 3):

- injection into the inlet pipe and measurement at the tank outlet.
- injection and measurement at the same point in the tank.

Measurements at the outlet permitted analysis of residence time distribution, whereas the in-tank configuration facilitated a more thorough investigation of the mixing process. Tank 1 was equipped with a fluorometer/injector assembly, which automatically injected Rhodamine WT into the system and measured fluorescence. Fig. 2 illustrates the overall layout of the experimental tank.

Water level was regulated using a central standpipe. The surrounding standpipe sleeve incorporated 2 holes at the base for egress of particulate materials. The fluorometer/injector assembly was placed directly opposite to the inlet. Tank water volume was 440 l. The tank had a diameter of 1.21 m and the water depth was maintained at 0.375 m. Flow was set at 0.23 l/s (1.9 exchanges/h) and 0.42 l/s (3.4 exchanges/h) in order to investigate mixing at high and low flow rates. The inlet was a single inlet with at diameter of 0.038 m. The inlet was located 0.23 m above the bottom of the tank, against the side wall. The inlet nozzle was pointed perpendicular to the radius. The dimensions of the tank and the fluorometer/injector assembly are noted Fig. 3. The tracer injection point was situated downstream of the fluorometer to avoid probe interference during injections. Signals from the fluorometer were measured with a PMD-1208LS

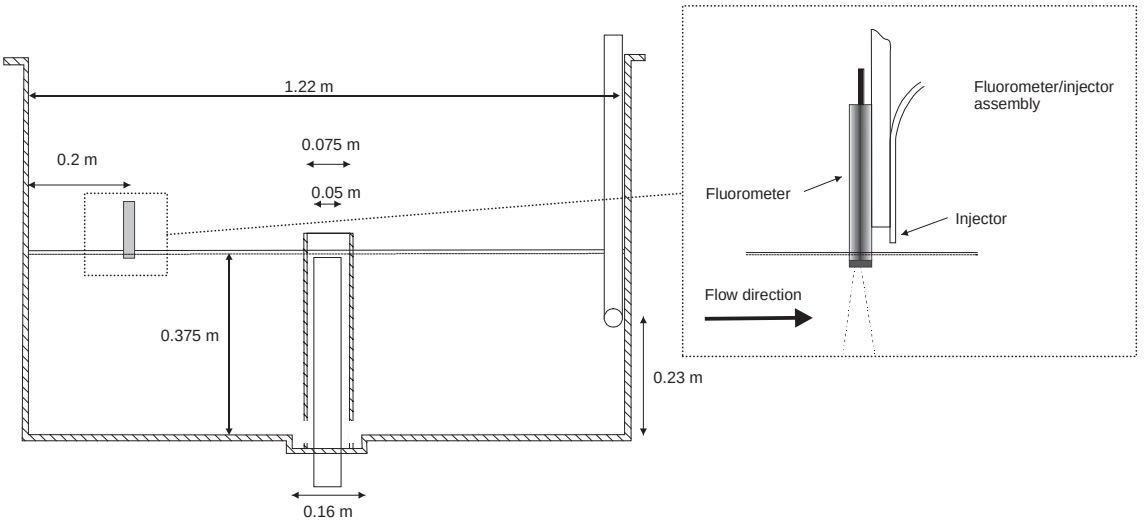


Fig. 3. Experimental tank dimensions and sketch of the fluorometer/injector assembly used in determining reactor mixing characteristics.

analog/digital board (Measurement Computing Corporation, Middleboro, MA, USA) and stored on a PC. Signals were sampled with a frequency of 1 Hz. Dedicated software was developed to acquire, store and analyze all measurements. Pump-based injection of Rhodamine WT tracer into the experimental tank was computer controlled. Using 4-h intervals, the software automatically injected 3 ml of dye (100 ppm Rhodamine WT) into the tank. Automation of this procedure minimized fish stress. Although the vast majority of Rhodamine WT was removed from the system water by the KMT bed and bead filter, measured background concentrations (residual Rhodamine WT) were subtracted from experimental data sets.

### 2.2. Methodological analysis of outlet tracer experiments

Measurement of dye concentrations at the outlet has traditionally been the preferred method to determine the mixing characteristics of non-idealized reactors. Calculation of tracer residence time allowed quantification of mixing.

Residence time, $\bar{t}$, was calculated as

$$\bar{t} = \frac{\int_0^\infty tC\mathrm{d}t}{\int_0^\infty C\mathrm{d}t} \tag{1}$$

where $C$ is the concentration and $t$ is time. Residence time was then compared to hydraulic residence time, $t_h$:

$$t_h = \frac{V}{Q} \tag{2}$$

where $V$ is the tank volume and $Q$ is the flow through the tank.

When the residence time is smaller than hydraulic residence time, this implies that not all of the tank volume participates in the process. This dead zone volume can be calculated as

$$V_{\text{dead zone}} = \left(1 - \frac{\bar{t}}{t_h}\right)V \tag{3}$$

Although difficult to identify physical positions of dead zones, their calculated size indicates the level of mixing occurring within a reactor or tank. Thus, it is impossible to have residence times that exceed hydraulic residence times.

If tank hydrodynamics resemble non-ideal plug flow characteristics, additional variables must be determined. It is assumed that the one-dimensional transport-dispersion model for conservative tracers in a stationary and uniform flow can be used.

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial C^2} \tag{4}$$

where $x$ is distance, $U$ the mean velocity, $D$ the dispersion coefficient, and $t$ is time.

Assuming that measured tracer concentration as a function of time is proportional to the concentration as a function of space, a simple relationship between tracer concentration variance and the dispersion number can be estimated (Levenspiel, 1999):

$$\frac{\sigma_t^2}{\bar{t}^2} = 2\left(\frac{D}{UL}\right) \tag{5}$$

where $\sigma_t^2$ is the variance calculated from the concentration measured at the outlet (Eq. (6)) and $L$ a characteristic length. The variance is calculated as

$$\sigma_t^2 = \frac{\int_0^\infty \left(t - \bar{t}\right)^2 C\mathrm{d}t}{\int_0^\infty C\mathrm{d}t}. \tag{6}$$

For higher dispersion numbers ($D/UL > 0.01$) in a closed reactor a correction to Eq. (5) is necessary (Levenspiel, 1999):

$$\frac{\sigma_t^2}{\bar{t}^2} = 2\left(\frac{D}{UL}\right) - 2\left(\frac{D}{UL}\right)^2\left(1 - \mathrm{e}^{-\left(\frac{UL}{D}\right)}\right). \tag{7}$$

The dispersion number can be determined by solving Eq. (7) iteratively. Variance and residence time is calculated using a numerical trapeze integration method. The dispersion number is dimensionless and indicates the proportion between dispersion and convection. The dispersion number will move asymptotically towards infinity as tank mixing approaches ideal mixed conditions. However, Levenspiel (1999) advocates that this method cannot be employed when the dispersion number exceeds 1. It should be noted that it remains impossible to isolate the dispersion coefficient from the dispersion number using this method, as it is unclear which characteristic length

and velocity should be employed. From theory, it is assumed that flow is one-dimensional and the characteristic length is the distance between the point of injection and the point of measurement and the characteristic velocity is the mean axial velocity. When measuring at the outlet in a circular tank, these values are not readily available. The dye tends to go in a rotational motion and not directly from inlet to outlet.

### 2.3. Methodological analysis of in-tank tracer experiments

As an option to the traditional methods of measurement and analysis of residence time distribution at the outlet of a circular tank, an alternative is proposed. Flow in circular tanks tends to be highly rotational. If a small amount of dye is injected into the tank, the dye will have a tendency to follow the same tangential streamline that it was injected into (Fig. 4). Due to centrifugal forces a secondary current slowly rotates the water in a cork-screw fashion. Thus, by taking measurements at the same distance from the center of the tank, portions of the cloud of dye can be assesed many times at different stages of dispersion.

The mathematical element for this method is the one-dimensional equation for transport-dispersion as described by Eq. (4). The analytical solution for Eq. (4), with an impulse injection of dye is (Fisher et al., 1979):

$$C(x,t) = \frac{M}{\sqrt{4\pi Dt}} \mathrm{e}^{\left(-\frac{(x-ut)^2}{4Dt}\right)} \tag{8}$$

where $M$ is the mass of dye injected in the cross-sectional area.

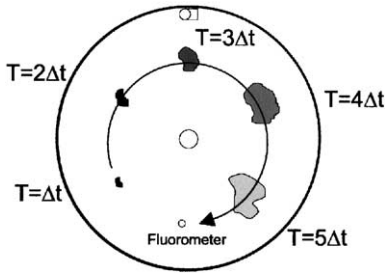


Fig. 4. Illustration of the dispersion characteristics of Rhodamine WT tracer as it circulated around the tank. The positions of the tank inlet and fluorometer-injector assembly are also noted.

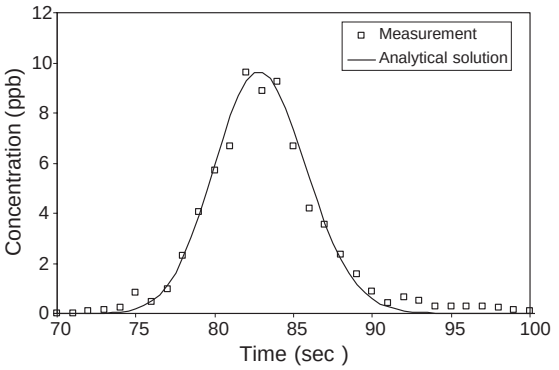


Fig. 5. An example curve fit for measured tracer concentrations and analytical solution, $R^2=0.98$.

Although it can be argued that tank dye dispersion is three-dimensional, a more detailed model is not justified unless the water velocity is measured more accurately and the transverse and vertical dispersion coefficients are found. The implication of this simplification is that the dispersion coefficient contains components of the vertical, transverse and longitudinal dispersion. However, this is not that different from real world application, such as pipe and river flows where Eq. (8) is widely used. The meandering of rivers results in rotational flows at their bends, which resembles the flow present in circular tanks and similar reactors.

The dispersion coefficient found from Eq. (8) can be split into separate components depending on the source of mixing:

$$D = D_x + D_{xy} + D_{xz} + D_i \tag{9}$$

where $D_x$ is the longitudinal mean dispersion coefficient, $D_{xy}$ and $D_{xz}$ are the longitudinal dispersion coefficient as a result of shear in the transverse and vertical plane, and $D_i$ is the longitudinal dispersion coefficient as a result of internal mixing (e.g., fish).

The present method was employed to determine the dispersion coefficient, $D$ in a tank with and without fish. Assuming that hydrodynamic-driven mixing ($D_x$, $D_{xy}$, $D_{xz}$) are identical in the two situations, the effect from fish can be determined by subtracting the dispersion coefficient without fish from the dispersion coefficient with fish:

$$D_i = D_{\text{with fish}} - D_{\text{without fish}} \tag{10}$$

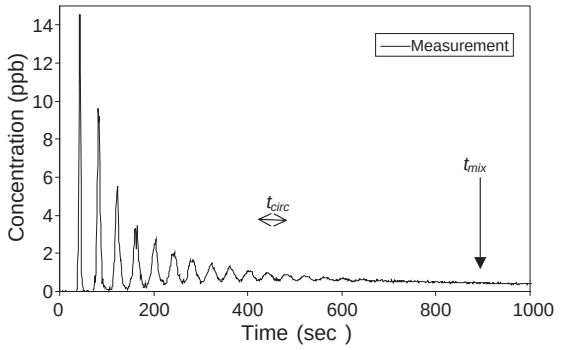


Fig. 6. Diagram illustrating the determination of circulation and mixing time. Mixing time, $t_{mix}$, was the time taken for the disappearance of harmonic variations. Mixing time was selected as the point at which the amplitude of the oscillation was ~10% of the mean value.

Eq. (4) assumes that the dye is evenly distributed over the cross section of the rotational flow. However, in this method the dye is injected at a single point in the tank. Comparison between analytical solutions for one- and three-dimensional transport-dispersion equations reveals that for small dispersion coefficients ($D \leq 0.1$ m$^2$/s), no significant differences exist. The one-dimensional equation can therefore adequately describe the mixing. For larger dispersion coefficients, however, a more elaborate analysis is required. The velocity and the dispersion coefficient are determined by fitting Eq. (8) to the measurements. Fig. 5 illustrates how the curve fits measurements from the circular tank without fish. By calculating the $R^2$, the best fit between curve and measurement can be found. The fit is completed using each individual peak, until individual peaks can no longer be observed. Fig. 6. exemplifies that the baseline of harmonic variations increases as a function of time. This baseline is subtracted from each peak prior to fitting the analytical solution.

The circulation time, $t_{\mathrm{circ}}$, can be found by calculating the center of gravity of each peak. The time period between two peaks represents the circulation time. Mixing time, $t_{\mathrm{mix}}$, represents the time taken for harmonic variations to disappear as illustrated in Fig. 6. For practical purposes, mixing time is selected as the point at which the amplitude of the oscillation is approximately 10% of the mean value. The dispersion number, which was established when taking measurements at the outlet can also be found using this method, provided that a characteristic length and velocity is determined. For flows such a pipe and channel flows, the pipe diameter or water depth is used.

The characteristic length in the case of a circular tank could be the water depth, $Y$. The characteristic velocity can be found as:

$$U = \frac{L_{\mathrm{circ}}}{t_{\mathrm{circ}}} \tag{11}$$

where $L_{\mathrm{circ}}$ is the length which the cloud of dye has to circulate before reaching the fluorometer again.

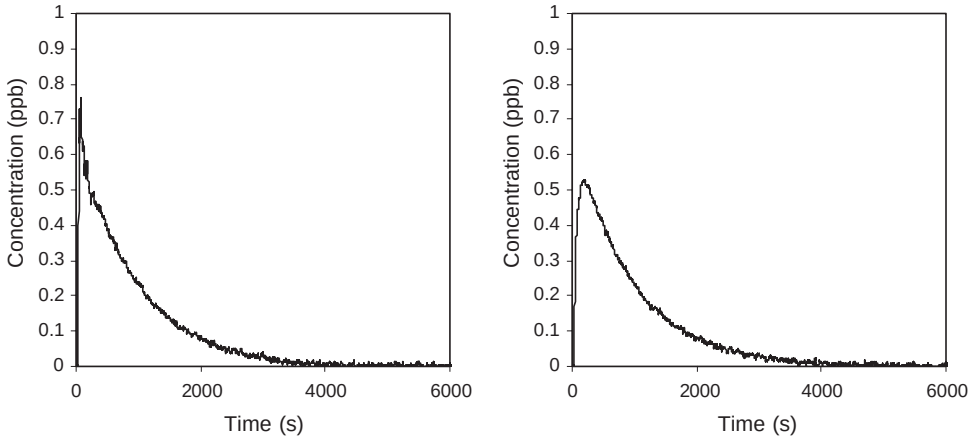


Fig. 7. Concentration of Rhodamine WT tracer measured at the tank outlet, either in the absence (left) or presence (right) of fish. The flow into the tank was 0.42 l s$^{-1}$.

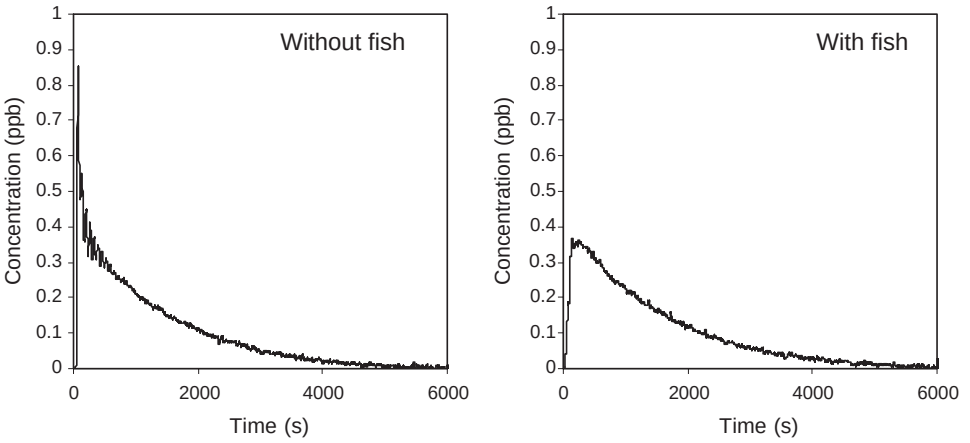


Fig. 8. Concentration of Rhodamine WT tracer measured at the tank outlet, either in the absence (left) or presence (right) of fish. The flow into the tank was 0.23 l $s^{-1}$.

The dispersion number can therefore be calculated as:

$$\left(\frac{D}{UL}\right) = \frac{D}{\left(\frac{L_{\text{circ}}}{t_{\text{circ}}}\right)Y}. \quad (12)$$

All results were analysed using Student's double-sided *t*-test.

## 3. Results

Example measured concentrations of Rhodamine WT at the outlet, either in the absence or presence of fish and with flow rates of either 0.42 or 0.23 l $s^{-1}$ are presented in Figs. 7 and 8. The figures both demonstrate that mixing within the tanks was excellent. However, in the presence of red drum, there was a noticeable smoothing of the curves, which was especially prevalent during the initial phase of the experiment.

Table 1 summarizes the results of all analyses with respect to mixing variables. Differences ($P<0.05$) were detected in hydraulic residence times for both flow rates examined due to the manual adjustments undertaken during the study. However, variances were low (Table 1). Irrespective of flow rate examined, increases ($P<0.001$) were observed in mean residence time ratios when red drums were present. Thus, these data clearly indicate that fish have explicit

Table 1
Mixing variables (±S.D.) determined at the outlet ($n=5$) at high and low flow rates and in the absence or presence of red drum in circular tanks containing a water volume of 440 l

| Flow | Mixing variable | Without fish | With fish |
|---|---|---|---|
| High flow | Hydraulic residence time, $t_h$ (min) | $17.40 \pm 0.005^a$ | $17.44 \pm 0.005^a$ |
| | Mean residence time ratio $t_c/t_h$ (–) | $0.89 \pm 0.011^b$ | $0.97 \pm 0.03^b$ |
| | Mixing time, $t_{mix}$ (min) | $8.06 \pm 0.58$ | ND |
| | Circulation time, $t_{circ}$ (min) | $0.57 \pm 0.012$ | ND |
| | Dispersion number, $D/uL$ (–) | $2.77 \pm 0.71$ | $2.55 \pm 0.85$ |
| Low flow | Hydraulic residence, $t_h$ (min) time | $31.40 \pm 0.005^a$ | $31.37 \pm 0.005^a$ |
| | Mean residence time ratio $t_c/t_h$ (–) | $0.71 \pm 0.034^a$ | $0.77 \pm 0.009^a$ |
| | Mixing time, $t_{mix}$ (min) | $15.93 \pm 0.44$ | ND |
| | Circulation time, $t_{circ}$ (min) | $1.09 \pm 0.019$ | ND |
| | Dispersion number, $D/uL$ (–) | $2.39 \pm 0.69^a$ | $1.37 \pm 0.27^a$ |

ND=not detectable. Presence of superscripts in rows indicates significant differences, with a indicating differences at the 0.05 level or better, and b indicating differences at a level of 0.001 or better. Mixing and circulation times are calculated.

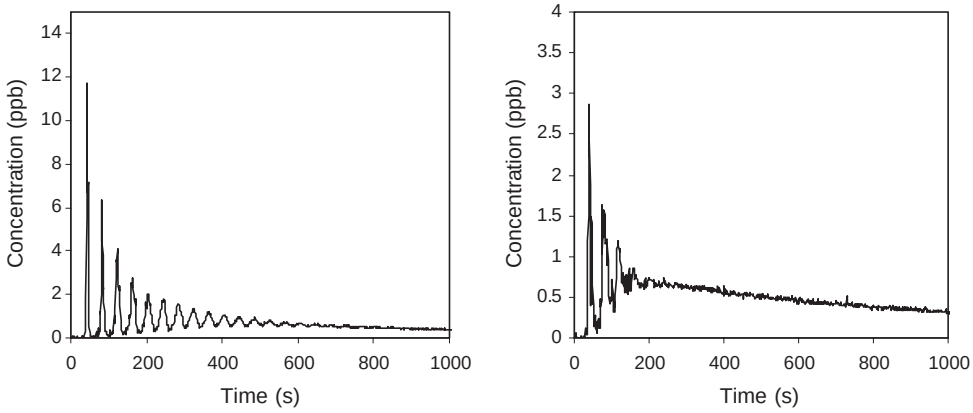


Fig. 9. Concentration of Rhodamine WT tracer measured using the in-tank method, either in the absence (left) or presence (right) of fish. The flow into the tank was 0.42 l $s^{-1}$.

impact upon tank mixing processes while also tending to decrease the occurrence of dead zones, as revealed by increased residency time for the tracer. At higher flows, the presence of fish had no impact ($P>0.05$) upon tank dispersion number. However, at low flow rates, addition of fish to the tank resulted in lower dispersion number ($P<0.001$). Noteworthy, however, was that the dispersion number was higher than suggested maxima (Levenspiel, 1999), such that the significance of these results remains questionable. Calculation of circulation and mixing times was only possible for tanks without fish. As might be anticipated, both circulation and mixing time at flows of 0.23 l $s^{-1}$ were approximately half those calculated for tank flow rates of 0.42 l $s^{-1}$.

Example measured concentrations of Rhodamine WT determined using the in-tank method, either in the absence or presence of fish, and with flow rates of either 0.42 or 0.23 l $s^{-1}$ are presented in Figs. 9 and 10. Lucid from these results is that a more detailed analysis of tank hydraulics is possible using in-tank measurements when compared to outlet studies. Thus, rather than permitting the construction of a single curvilinear relationship (Figs. 7 and 8), in-tank measurements provided the means to examine the kinetics of tracer mixing over time. Comparison of in-tank measurements with those taken only at the outlet illustrate that tank mixing is extremely dynamic during the first 400–600 s of the process. This progression is not possible to discern using outlet

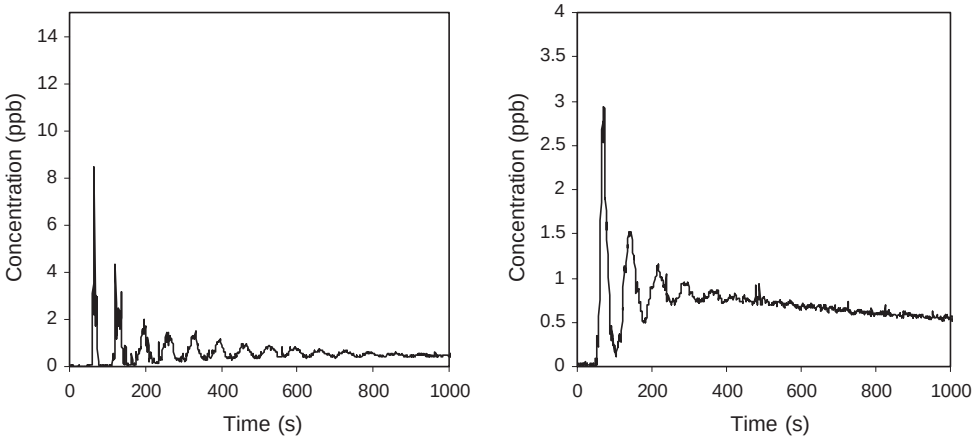


Fig. 10. Concentration of Rhodamine WT tracer measured using the in-tank method in the absence (left) or presence (right) of fish. The flow into the tank was 0.23 l $s^{-1}$.

Table 2
Mixing variables (±S.D.) determined using in-tank determinations ($n=6$) at high and low flow rates and in the absence or presence of red drum in circular tanks containing a water volume of 440 l

| Flow | Mixing variable | Without fish | With fish |
|---|---|---|---|
| High flow | Hydraulic residence time, $t_h$ (min) | $17.38 \pm 0.005^b$ | $17.53 \pm 0.005^b$ |
| | Mixing time, $t_{mix}$ (min) | $12.24 \pm 0.31^b$ | $4.41 \pm 0.38^b$ |
| | Circulation time, $t_{circ}$ (min) | $0.67 \pm 0.0067$ | $0.64 \pm 0.028$ |
| | Dispersion coefficient, $D$ ($m^2/s$) | $0.0002125 \pm 0.000064$ | $0.000975 \pm 000104^b$ |
| | Dispersion number, $D/uL$ (–) | $0.00133 \pm 0.00038^b$ | $0.00573 \pm 0.00059^b$ |
| Low flow | Hydraulic residence time, $t_h$ (min) | $31.25 \pm 0.005^b$ | $31.97 \pm 0.005^b$ |
| | Mixing time, $t_{mix}$ (min) | $19.29 \pm 0.69^b$ | $6.35 \pm 0.59^b$ |
| | Circulation time, $t_{circ}$ (min) | $1.05 \pm 0.031$ | $1.11 \pm 0.024$ |
| | Dispersion coefficient, $D$ ($m^2/s$) | $0.000142 \pm 000081$ | $0.000706 \pm 0.000174^b$ |
| | Dispersion number, $D/uL$ (–) | $0.00139 \pm 0.00079^b$ | $0.00720 \pm 0.00186^b$ |

ND=not detectable. Presence of superscripts in rows indicates significant differences, with *a* indicating differences at the 0.05 level or better, and *b* indicating differences at a level of 0.001 or better.

only measurements (cf. Figs. 7 and 9 and Figs. 8 and 10). Nevertheless, like the outlet only determinations, in-tank measurements further highlight the influence that fish have upon the tank mixing process.

Table 2 summarizes the results of all analyses with respect to mixing variables using the in-tank method. Although the presence of fish had no impact upon circulation times ($P>0.05$), significant effects were observed for all other variables examined. Thus, regardless of flow employed, the presence of fish was seen to dramatically decrease ($P<0.001$) mixing times by as much as one-third. Increased dispersion coefficients ($P<0.001$) were observed for both flow regimes when red drums were present.

## 4. Discussion

One of the principal motivations underlying animal domestication is to enhance production. An important component during this process is the selection of animals that are able to perform well in artificial environments (Price, 2002). Animal agriculture has over a 10,000-year history of selection (Jones and Brown, 2000) and the performance characteristics of terrestrial stocks have been immensely improved. In stark contrast, it has been estimated that only 1–2% of all aquacultured species have experienced genetic selection (Gjedrem, 1997). Ostensibly then, the vast majority of aquaculture production is reliant upon feral, or close-to-wild stocks. The coping styles (Koolhaas et al., 1999) or adaptive capabilities of feral populations are often restricted in scope such that an onus is placed upon the systems engineer to design appropriate rearing units that allow optimal production efficiency for individual species. In this context, attention to tank hydraulics becomes important because fish express a wide range of behaviors that may, to a certain extent, be positively influenced by hydrodynamic control. For example, territoriality, aggressive and boundary responses can be beneficially manipulated in salmonids by attention to stocking density and adjustments to water flow (Ross et al., 1995). Similarly, a detailed understanding of tank mixing can be gainfully employed to optimize feeding activities and actions, establish efficient sludge removal and ensure correct dissolution of water treatments (Rasmussen et al., 2004).

Accurate determination of tank mixing, however, is problematic. Conventionally, researchers have employed outlet measurements to characterize changes in mean residency time and dispersion number. However, observations from the present studies provide strong evidence to suggest that the in-tank method represents a superior technique for evaluating the impact of fish upon tank hydrodynamics. This method provided improved data acquisition and also presented the means to more readily discriminate, statistically, differences in mixing caused by the presence of fish. Importantly, the method described herein permitted sampling frequencies high enough to detect harmonic variations of tracer within the tank. The current studies clearly demonstrated that irrespective of flow rate, the presence of fish enhanced tank mixing. Moreover, the time taken to achieve complete tank mixing ($t_{mix}$) was at least two-thirds less in tanks

with fish than in tanks without. Employing in-tank measurements determined that the presence of fish greatly enhanced tank dispersion coefficients for both flows examined. In contrast, at high flows and in the presence of fish, no differences were seen in dispersion number when measuring at the outlet only. However, at low flows, the presence of fish caused reductions in dispersion number. Failure to detect differences in dispersion number using outlet measurements alone has likewise been reported by Watten and Beck (1987), who used circular tanks with channel catfish and employed similar residence times to the study described herein. Distinct to the investigations here and to those of Watten and Beck (1987) are the findings of Watten et al. (2000), who stated that the presence of lake trout decreased mixing in circular tanks. This deduction was made at even lower flow rates than employed by the present study, using outlet measurements only.

Comparisons of dispersion number from the present experiments without fish illustrate that irrespective of flow, these remained the same. This observation fits well with theory for one-dimensional flows where dispersion number becomes constant at higher Reynolds numbers (Levenspiel, 1958). Introduction of fish into the system, however, altered this dynamic. Fish presence in this instance thus represents an important facet of the hydrodynamic environment. Although outlet-based (one peak) determination of dispersion number provided accurate system evaluation, it was only with in-tank determinations that the discrete impact of fish upon the mixing process could be appreciated. A number of studies suggest that through hydrodynamic sensing, teleosts and other aquatic species undertake subtle adjustments in posture, movement and positioning to facilitate favorable exploitation of variations in the hydrodynamic environment (Shtaf et al., 1983; Anderson et al., 2001; Webb, 2002). One benefit that arises from hydrodynamic repositioning is a reduction in the energetic costs of locomotion. This may be achieved through the fine-tuning of standard metabolic rates (SMR; Pettersson and Hedenstrom, 2000; Liao et al., 2003), or through fish, especially when in schools, taking hydromechanical advantage of vortex streets (Weihs, 1973; Blake, 2004; Tytell and Lauder, 2004). Hydromechanical adjustments and or refinement to SMR may provide partial explanations for the beneficial effects that have been observed to accrue following exercise training of fish (e.g., improved: fitness, growth homogeneity, body composition, food conversion and muscle growth and reduced aggression; Jørgensen and Jobling, 1993; Hammer and Schwarz, 1994; Azuma et al., 2002). Preservation of position, especially in higher flows necessarily involves simultaneous use of multiple fins and body flex (Breder, 1926) which will result in subtle adjustments to swimming forces, resulting in the creation of localized jets and vortices. Maintenance of stability within the water column thereby demands control of both external and self-generated alterations to the aquatic medium. Stability control requires precise body and fin movements which will inevitably create significant, albeit confined perturbations in the water column (Drucker and Lauder, 2003). These movements may provide one explanation for the enhanced tank mixing process noted when fish were present.

Videography undertaken during the present experiments revealed that changes in flow regimes resulted in red drum repositioning within the water column. At low flow, fish expressed random movement and direction, whereas at high flow, animals relocated to positions near the tank base and close to its wall; also, animals positioned in a unidirectional manner, swimming against the flow. Theoretically, changes in fish station, caused by higher flow rates, could have reduced fish-tracer interactions which in turn might have influenced mixing time and dispersion coefficient. Unequivocal is that the presence of fish greatly enhanced tank mixing. Although the data from this study illustrates the impact that fish have upon tank hydrodynamics, it is noteworthy that together with stocking density, tank design will also impact fish hydrodynamics and their overall production efficiency. The present study illustrated that fish presence induced measurable and enhanced mixing in circular tanks. Moreover, in-tank data acquisition appeared superior to outlet measurements when taking account of the impact of fish upon the mixing process. Clearly, different stocking densities, fish sizes and species will impart diverse influences upon tank mixing processes and a more precise understanding of such impacts will assist in the design of optimal species-specific rearing units.

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