HYDRODYNAMIC CHARACTERISATION OF AQUACULTURE TANKS AND DESIGN CRITERIA FOR IMPROVING SELF-CLEANING PROPERTIES

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2. PUBLISHED ARTICLES INCLUDED IN THIS DISSERTATION

2.1. Oca, J., **Masaló I.**, Reig, L. (2004) *Comparative analysis of flow patterns in aquaculture rectangular tanks with different water inlet characteristics.* Aquaculture Engineering 31 (3-4), pp 221-236

2.2. Oca, J., **Masaló, I.** (2007) *Design criteria for rotating flow cells in rectangular aquaculture tanks.* Aquacultural Engineering 36 (1), pp 36-44

2.3. Masaló, I., Reig, L., Oca, J. (2008) *Study of fish swimming activity using Acoustical Doppler Velocimetry (ADV) techniques.* Aquacultural Engineering 38 (1), pp 43-51

2.4. Masaló, I., Guadayol, O., Peters, F., Oca, J. (2008) *Analysis of sedimentation and resuspension processes of aquaculture biosolids using an oscillating grid.* Aquacultural Engineering 38 (2), pp 135-144

1. GENERAL INTRODUCTION

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1.1. REQUIREMENTS OF FISH-REARING TANKS

Aquaculture production units should be designed to create a restricted volume in which aquatic organisms can be reared under the best possible conditions for growth. To make aquaculture compatible with environmental restrictions and with other important economic activities such as tourism or fishing, tanks must guarantee fish welfare, minimise resource consumption (feed, oxygen, energy) and labour costs, cause minimal environmental impact and occupy the smallest area possible.

Rearing tanks are the physical rearing areas in land-based systems. Adapting tank designs to the specific behaviour or swimming activity of the species used, which reduces stress levels and improves fish welfare, can enhance fish growth. In addition, homogeneous water quality makes it possible to take further advantage of the whole rearing volume, the water flow and the oxygen added to the water, and ensures that all areas of the tank provide optimum rearing conditions.

According to Tvinnereim (1988), Cripps and Poxton (1992), and Timmons et al. (1998), an adequate tank design should provide uniformity of rearing conditions, fast elimination of biosolids (non-ingested feed and faeces) and uniform distribution of fish throughout the tank.

A fourth condition should be added to ensure that the velocities in the tank are optimal for maintaining fish health, muscle tone and respiration. This condition improves the overall fish welfare and the quality of the final product.

The tank hydrodynamics determine whether these conditions are met and govern the efficiency of resource and water use; in turn, the tank hydrodynamics are determined by the water inlet and outlet configurations and the degree of fish swimming activity.

Fish swimming activity is given particular importance here as it has not been considered in detail in many other studies (Rasmussen et al., 2005; Lunger et al., 2006). Fish behaviour and swimming activity are, at time, influenced by tank hydrodynamics, which can produce heterogeneous conditions by inducing fish to distribute heterogeneously throughout the tank (Ross et al., 1995; Ross and Watten, 1998).

1.2. TANK HYDRODYNAMICS

The hydrodynamics of an aquaculture tank should create homogeneous rearing conditions, facilitate cleaning, and generate the appropriate velocities for the size and species of fish reared.

Since the 1950s the study of tank hydrodynamics has been developed (Burrows and Chenoweth, 1955). Since then, many authors have carried out research in the field, focusing particularly on tank geometry (Wheaton, 1977; Klapsis and Burley, 1984; Burley and Klapsis, 1985; Watten and Beck, 1987; Watten and Johnson, 1990; Timmons and Youngs, 1991; Cripps and Poxton, 1992, 1993; Lawson, 1995; Ross et al., 1995; Timmons et al., 1998; Watten et al., 2000) and water inlet and outlet characteristics (Tvinnereim, 1988; Watten et al., 2000; Davidson and Summerfelt, 2004; Labatut et al., 2007b).

Two tank geometries are commonly used in aquaculture: rectangular and circular. Water generally flows from the upper to the lower end of rectangular tanks. The minimum waste concentration is found in the area around the water inlet and the maximum concentration at the outlet. Gradients of environmental conditions are observed between the two points (Watten and Johnson, 1990), which often lead to heterogeneous fish distribution (Ross and Watten, 1998).

In circular tanks, water is usually injected tangentially to the wall, which creates a rotating flow cell that provides highly uniform water quality conditions (Westers and Pratt, 1977; Ross et al., 1995) due to the effective mixing achieved (Ross and Watten, 1998; Timmons et al., 1998). The water outlet is usually placed in the bottom centre of the tank, which produces self-cleaning properties because the circular flow pattern rapidly flushes biosolids to the central outlet (Skybakmoen, 1989; Tvinnereim and Skybakmoen, 1989; Timmons et al., 1998).

Levenspiel (1966) defined two ideal types of flow in reactors: plug flow and mixing flow. In mixing flow, the fluid has the same characteristics inside the tank as at the outlet because the particles mix as soon as they enter the tank. In plug flow, no mixing or diffusion occurs along the flow path and the flow particles enter and leave the tank in the same order. Circular tanks produce a flow pattern similar to mixing flow, whereas rectangular tanks are often designed to provide plug flow, although the real conditions can vary significantly in practice.

1.2.1. Circular rearing tanks

Circular tanks with tangential water inlets generally produce a uniform flow pattern and high velocities (Ross and Watten, 1998) with lower exchange rates than in rectangular tanks. The high degree of mixing leads to a more even distribution of fish (Ross et al., 1995; Ross and Watten, 1998), which optimises the use of water and space.

Despite the uniform flow pattern produced in circular tanks, several studies have focused on the effect of the water inlet on solid flushing, water mixing, and water velocity profiles inside the tanks (Tvinnereim and Skybakmoen, 1989; Davidson and Summerfelt, 2004), and on the effect of the diameter/depth ratio (Larmoyeux et al., 1973) on flow pattern. Finally, devices designed to facilitate the removal of solid wastes by concentrating them in a small percentage of water effluent were introduced in the 1990s (Van Toever, 1997; Lunde et al., 1997; Schei and Skybakmoen, 1998).

In circular tanks, water inlet designs with a single point source produce less homogeneous flow distribution (Larmoyeux et al., 1973) than configurations with a vertical pipe containing nozzles that are distributed along the water column (Tvinnereim and Skybakmoen, 1989; Watten et al., 2000; Labatut et al., 2007a; 2007b). The mixing efficiency in the tank depends to a certain extent on the direction of the flow injection nozzles (Davidson and Summerfelt, 2004).

The diameter/depth ratio in circular tanks affects the homogeneity of the conditions. If the ratio becomes too low (i.e. in deep tanks), a torus-shaped area can appear about the centre drain, which develops into an irrotational zone that generates lower velocities and poor mixing (Larmoyeux et al., 1973; Timmons et al., 1998). Larmoyeux et al. (1973) recommended using diameter/depth ratios of between 5:1 and 10:1 to prevent the appearance of irrotational zones. However, the diameter/depth ratio is also determined by the cost of floor space, the water head, the fish stocking density, the fish species, the feeding levels and the type of handling required (Timmons et al., 1998).

Dual-drain systems are now used in circular tanks to concentrate wastes and simplify the water treatment. The particles are collected using a small amount of water (secondary or concentrated flow) from the bottom of the tank, while the main water flow (clarified flow) is removed via an elevated drain and is usually recirculated. In dual-drain systems, only 5-20% of recirculating water is drained from the bottom centre of the tank (secondary flow) but 80-90% of suspended solids is removed (Van Toever, 1997; Lunde et al., 1997; Schei and Skybakmoen, 1998; Summerfelt et al., 2000; Davidson and Summerfelt, 2004).

Several types of dual-drain systems have been designed. In most cases, both the main and secondary flows are withdrawn from the tank centre (Lunde et al., 1997; Schei and Skybakmoen, 1998; Van Toever, 1998), whereas in other systems (e.g. Cornell–type dual-drain tank) the secondary flow was withdrawn from the centre of the tank bottom but the main flow was withdrawn through an elevated drain in the side wall (Timmons et al., 1998). Poor tank mixing is observed when the main flow is removed from the side wall, because short-circuiting is often created along the side wall from the water injection point to the drain. Higher fish densities can improve mixing in these configurations (90-98 kg m^{-3}) (Lekang et al., 2000; Davidson and Summerfelt, 2004).

Although circular tanks produce more homogeneous conditions and higher velocities than rectangular tanks with the same power requirements, they are less widely used in aquaculture facilities because they require more space and are more labour-intensive on a daily basis.

1.2.2. Rectangular rearing tanks

Rectangular tanks, in which water flows from the upper to the lower end, can sometimes present unpredictable flow patterns. The conditions inside the tank are generally non-uniform, in particular close to the water inlet, which reduces the efficiency of water use and makes waste treatment more difficult. High water-exchange rates are needed to produce self-cleaning conditions inside the tank (Westers and Pratt, 1977; Youngs and Timmons, 1991), which means that the energy requirements are higher than in circular tanks. Biosolid sedimentation on the tank bottom is often found in areas with lower water velocities and low fish densities. However, linear raceways (rectangular tanks made of concrete with a length-width ratio greater than 5:1) are one of the most popular tank designs for fish production, mainly because they utilise the available area much more efficiently than circular tanks and are easier to handle and sort fish. Raceways are also easier to construct, handle and adapt to common plot geometries. The characteristics and location of the water inlets and outlets determine the flow pattern, and many authors have tried to incorporate some of the advantages of circular tanks by using the inlets and outlets to create a rotating flow pattern.

Watten and Beck (1987) designed the cross-flow tank (Figure 1.1), which uses the rectangular geometry of a conventional raceway tank but provides the hydraulic characteristics of a mixing-flow configuration. In a cross-flow tank, water is jetted directly at the water surface to induce rotatory circulation along the longitudinal axis. However, this can also create a bypass current or short-circuiting in the bottom of the tank. The cross-flow tank eliminates the fish distribution gradient that is present in plug-flow tanks (Watten and Johnson, 1990) and which often creates hierarchies and stimulates aggressive behaviour (Ross et al., 1995; Ross and Watten, 1998).

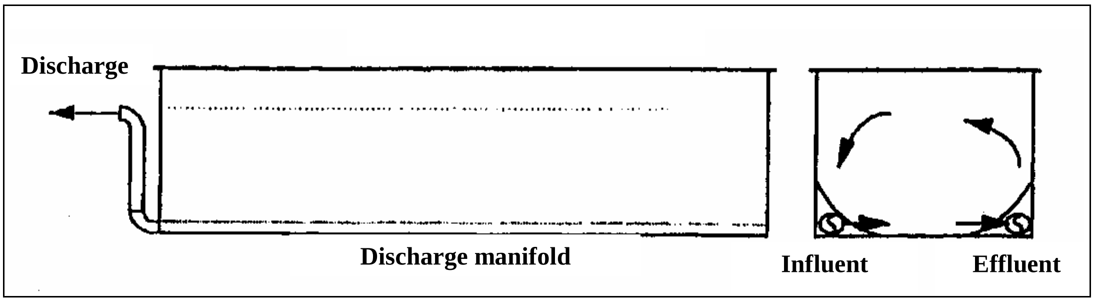

Figure 1.1: The cross-flow tank (Watten and Beck, 1987).

Watten et al. (2000) designed a new tank called mixed-cell raceway that creates horizontal mixed-rotating cells (Figure 1.2). The design was also intended to combine the best characteristics of circular and rectangular tanks in a single system. Linear raceways were converted into a series of hydraulically separated cells with an outlet (drain) in the bottom centre of each cell, which enabled each one to operate as an individual circular tank. No dead volumes or short-circuiting were observed in the cells, which indicates that an adequate degree of mixing is achieved (Labatut et al., 2007a). The design therefore combined the high biosolids removal of circular tanks with the easier handling of rectangular tanks. The jet velocity and nozzle diameter are the main variables that need to be controlled in this type of configuration (Labatut et al., 2007b).

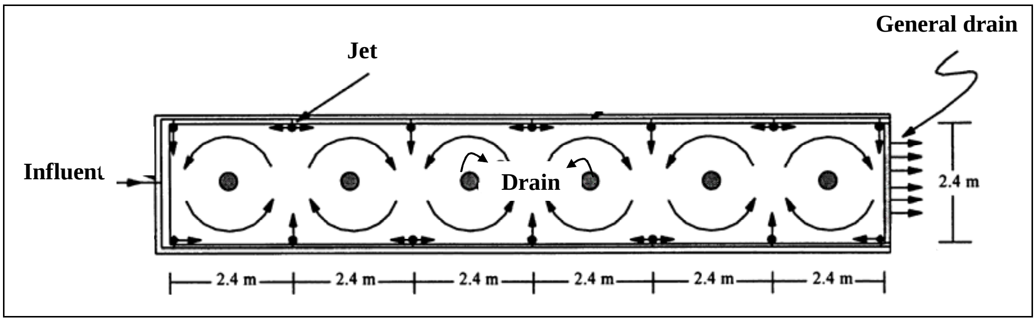

Figure 1.2: The mixed-cell raceway (Watten et al., 2000).

Another strategy for improving biosolids removal in rectangular tanks is to use vertical baffles to increase velocity and facilitate the removal of settled biosolids (Westers and Pratt, 1977; Boerson and Westers, 1986; Kindschi et al., 1991; Barnes et al., 1996; True et al., 2004). However, baffles can also contribute to fin erosion (Barnes et al., 1996) and affect the distribution of fish size in the tank (Kindschi et al., 1991).

New rectangular tank designs have been used since the 1990s to increase the efficiency of water consumption and to optimise the use of space. Examples include the shallow raceway systems (SRSs) developed by Strand and ∅iestad (1997). SRSs typically use a very shallow water depth (tested with water levels of 7 mm for fish of approximately 100 mg, and 25 cm for fish above 2 kg), high velocities and high densities (∅iestad, 1999). The main disadvantage of this design is the low oxygen level in the tank due to the small volume of water volume used, which leads to a very short response time if the oxygenation system fails. Oxygen supersaturation must therefore be maintained at the water inlet, which increases the losses due to diffusion between the air and water.

Several devices have been developed for concentrating solid wastes in rectangular systems. Wong and Piedrahita (2003) described a device that is placed close to the water outlet in raceways and creates the same effect as a dual-drain system (typical of circular tanks). The device produces rotational velocities downstream of the raceways, sweeps stable solids towards collection areas, and is capable of removing 40-50% of the settleable material with 5-10% of the total water circulating.

1.2.3. Velocity in rearing tanks

If the velocities inside a tank can be controlled, it is easier to adjust the tank configuration to produce the desired fish swimming speed for maintaining general health, muscle tone and respiration, which varies according to the size and species of fish (Woodward and Smith, 1985; Watten and Johnson, 1990; Timmons and Youngs, 1991; Losordo and Westers, 1994). The velocity in the tank also needs to be controlled to make sure that the tank bottom is free of biosolids, since these waste particles consume oxygen and could create hypoxic conditions.

A good water inlet and outlet design allows users to control the velocities and, by extension, the general flow conditions inside the tank (Tvinnereim and Skybakmoen, 1989). The water velocity needed to maintain self-cleaning properties ranges from 3 to 40 cm s^{-1} varying greatly according to the physical properties of the biosolids (Burrows and Chenoweth, 1970; Boersen and Westers, 1986; Tvinnereim, 1988; Timmons and Young, 1991). The presence of fish in the tank can reduce the velocities needed to maintain self-cleaning properties, since more efficient cleaning has been demonstrated in circular tanks stocked with fish (Timmons et al., 1998; Lekang et al., 2000).

For salmonids, the optimal velocities for fish health were found to be between 0.5 and 2 times the fish body length per second (BL s^{-1}) (Timmons and Youngs, 1991; Losordo and Westers, 1994). The higher swimming speeds that can be attained in circular tanks were found to improve the growth rate and food conversion efficiency of teleost fish (Davison, 1997). Timmons and Youngs (1991) provided the following equation for predicting safe, non-fatiguing water velocities for salmonids:

$$v_{safe} \leq \frac{5.25}{BL^{0.37}} \qquad \textbf{Equation 1.1}$$

where BL is the fish body length in cm and v_{safe} is the maximum design velocity (approximately 50% of the critical swimming speed) in fish body lengths s^{-1}.

The average velocity in rectangular tanks can be calculated easily using Equation 1.2:

$$v = \frac{R\,L}{3600} \qquad \textbf{Equation 1.2}$$

where v is the velocity (m s^{-1}), R is the rate of exchange (h^{-1}) and L is the length of the raceway (m).

However, the local velocity magnitudes can vary considerably from the average velocities in the longitudinal axis, due to the presence of unexpected eddies and dead volumes.

The average velocity around the centre of a tank with a circular flow pattern is controlled by the impulse force and affected by the water inlet discharge and velocity (Tvinnereim and Skybakmoen, 1989) (Equation 1.3):

$$F_i = \rho Q(v_2 - v_1) \qquad \textbf{Equation 1.3}$$

where F_i is the impulse force, ρ is the density, Q is the discharge, v_2 is the water velocity inlet and v_1 is the mean circulation velocity.

Variations in discharge (flow rate) and section of water inlet orifices affect the impulse force and therefore control the horizontal circulation velocity. Timmons et al. (1998) reported that the mean circulation velocity (v_1) is proportional to the inlet velocity (v_2) for a specific circular tank.

1.2.4. Study of tank hydrodynamics

There are various techniques for studying tank hydrodynamics. The most common techniques in the aquaculture field are residence time distribution (RTD) analysis (Burley and Klapsis, 1985; Watten and Beck, 1987; Watten and Johnson, 1990; Cripps and Poxton, 1993; Watten et al., 2000; Rasmussen and

McLean, 2004; Rasmussen et al., 2005; Lunger et al., 2006) and tracer tests in which the tracer concentration is measured at different points in the tank (Burrows and Chenoweth, 1955; Tvinnereim, 1988; Tvinnereim and Skybakmoen, 1989).

RTD provides accurate information about the flow behaviour inside tanks. The residence time of an element of fluid is the amount of time it spends in the vessel or tank, which is evaluated by examining the temporal evolution of a tracer that has been added to the tank (Levenspiel, 1966). Different fluid elements spend different amounts of time in the tank, so a distribution of residence times is produced. RTD curves are obtained by injecting a known amount of tracer at the water inlet and measuring the tracer concentration at the outlet. The technique is used to assess tank mixing and detect bypass currents and dead volumes and can be carried out while fish are present. However, RTD analysis cannot provide a detailed model of the velocity field.

Tank hydrodynamics can also be studied by taking water velocity measurements at several points. The measurements can be taken using propeller velocity probes (Burley and Klapsis, 1985), electromagnetic current meters (Watten et al., 2000) or new techniques such as acoustic Doppler velocimetry (ADV), which was introduced in the 1990s. ADV has been used to measure water velocity in aquaculture tanks (Odeh et al., 2003; Davidson and Summerfelt, 2004; Labatut et al., 2007a; 2007b) and in quiescent zones (Viadero et al., 2005). Acoustic Doppler velocimeters provide accurate flow measurements, but the measurement points should not be too high in the tank. In addition, the probe can disrupt the flow. Water velocity measurements at a specific point can be taken while fish are present, although there are some restrictions and it must be taken into account that fish activity could affect the results.

Computational fluid dynamics (CFD) can be used to describe the flow field in a tank in two or three dimensions, but the results need to be verified in subsequent laboratory or field studies. This technique has been used in river engineering (Nicholas and Smith, 1999), in sedimentation tank design (Stovin and Saul, 1996, 1998; Faram and Harwood, 2002; Adamsson et al., 2003), in the study of flow patterns in open channels (Wu et al., 2000), and in the field of aquaculture to study water flow and sediment transport in raceways (Peterson et al., 2000; Huggins et al., 2004; 2005).

Other techniques introduced in the 1990s include particle velocimetry techniques such as particle tracking velocimetry (PTV). PTV is a non-intrusive method in which tracer particles are used to describe the flow pattern. Its main advantage is that a full flow field is obtained in a two-dimensional cross section of flow after image processing. However, it cannot be used in large tanks or when fish are present, since the tracer particles could harm them. PTV techniques have been used successfully in different fields of engineering (Sveen et al., 1998; Grue et al., 1999; Uijttewaal, 1999; Montero et al., 2001, Chang et al., 2002). The method has not yet been used to evaluate flow patterns in aquaculture tanks.

Although some of these techniques can be used in real (field-scale) facilities (Table 1.1), most analyses are made at the laboratory scale because modifications can be made more easily and more quickly. The results obtained with models are then transferred to larger tanks so that the scale effects can be evaluated.

Table 1.1: Techniques used to study tank hydrodynamics and range of applications.

Technique	**Full flow field**	**Laboratory scale**	**Field scale**	**With fish**
Residence time distribution	NO	YES	YES	YES
Velocity measurement at a given point	NO	YES	YES	With restrictions
Particle velocimetry techniques	YES	YES	NO	NO
Computational fluid dynamics	YES	--	--	--

The flow conditions in a physical model are comparable to those in the prototype if the model has a similar shape (geometry), motion (kinematics) and forces (dynamics). Similarity analysis is essential for transferring results to other, geometrically similar tanks at a different scale.

Geometric similarity is determined by the length (L), area (A) and volume (V) of the tank. The characteristic length ratio (λ_L, Equation 1.4) between full-scale (L_F) and model (laboratory-scale) tanks (L_M) must be constant for similarity to exist.

$$\lambda_L = \frac{L_F}{L_M}$$

Equation 1.4

Kinematic similarity implies that the ratios between characteristic full-scale (v_F) and model velocities (v_M) must be constant (λ_v) (Equation 1.5). Dynamic similarity also implies a constant ratio (λ_F) between full-scale (F_F) and model forces (F_M) (Equation 1.6).

$$\lambda_v = \frac{v_F}{v_M}$$

Equation 1.5

$$\lambda_F = \frac{F_F}{F_M}$$

Equation 1.6

Froude and Reynolds numbers are the main criteria used when the results from hydrodynamic studies with a tank model are transferred to a full-scale prototype.

The Reynolds number relates the inertial forces to the viscous forces (Equation 1.7):

$$\mathrm{Re} = \frac{vL}{\upsilon}$$

Equation 1.7

where v is the water velocity, L is the characteristic length (usually water depth) and υ is the kinematic fluid viscosity.

By scaling up model velocities using the Reynolds criteria, we obtain

$$v_M L_M / \upsilon_m = v_F L_F / \upsilon_F ,$$

and by taking $\upsilon_M = \upsilon_F$,

we obtain $v_F = v_M L_M / L_F = v_M \lambda_L^{-1}$.

The Froude number relates the inertial forces to the gravitational forces (Equation 1.8) and is the most common dimensionless number used in open-channel hydraulics (free-surface flow); gravitational effects are dominant, so the effect of viscosity can be disregarded:

$$Fr = \frac{v}{(gL)^{1/2}} \qquad \textbf{Equation 1.8}$$

where *v* is the water velocity, *L* is the characteristic length (usually water depth) and *g* is the acceleration due to gravity.

By scaling up the model velocities using the Froude criteria, we obtain

$$v_M / g_M^{1/2} L_M^{1/2} = v_F / g_F^{1/2} L_F^{1/2} ,$$

and by taking $g_M = g_F$,

we obtain $v_F = v_M \left(L_F / L_M \right)^{1/2} = v_M \lambda_L^{1/2}$.

The velocity obtained for a particular fluid (identical viscosity) will differ considerably depending on whether the Froude or Reynolds criteria are used (according to the Reynolds criteria, $v_F = v_M \lambda_L^{-1}$; according to the Froude criteria, $v_F = v_M \lambda_L^{1/2}$).

Care should be taken when transferring results. Laboratory models with high Reynolds numbers are often used to minimise the influence of viscous forces on the flow. Consequently, it is common to use the Froude criteria and to verify the error induced by the effect of viscous forces in full-scale prototypes.

1.2.5. Effect of fish swimming activity on tank hydrodynamics

Fish swim either by body/caudal fin (BCF) movements or median/paired fin (MPF) propulsion (Videler, 1993). When fish swim, the surrounding water moves at the same velocity. Water beyond the boundary layer is not dragged along in the swimming direction, and a velocity gradient is generated, which causes free shear.

When the flow changes from laminar to turbulent, water sheets that move at different velocities fail to follow the contour of the body and the flow separates into circulating masses of water called eddies or vortices (Figure 1.3), which increase turbulence and mixing.

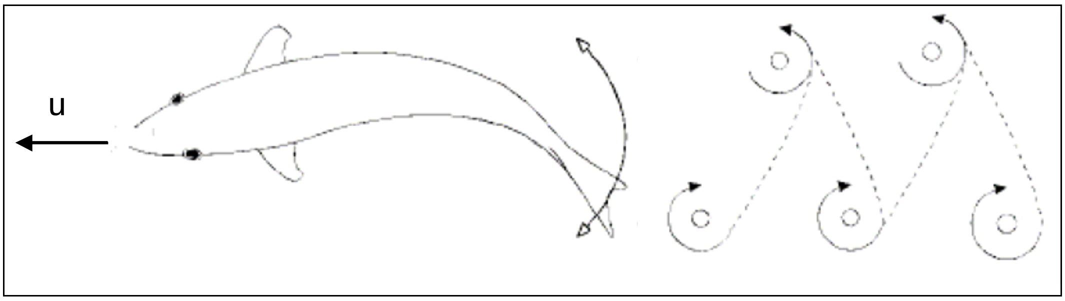

Figure 1.3: Eddies generated behind a swimming fish. A jet flow with alternating direction between the vortices can be seen (Sfakiotakis et al., 1991).

The turbulence generated by fish movement affects the tank hydrodynamics. Studies have been carried out to analyse the effect of fish activity and distribution on water homogeneity (Davidson and Summerfelt, 2004; Rasmussen et al., 2005; Lunger et al., 2006) and sediment dynamics (Brinker and Rösch, 2005). Fish activity can have a significant effect on tank mixing, particularly in intensive farming systems where high fish densities are common. Higher fish densities generate higher turbulence (Lunger et al., 2006), which can often be sufficient to keep biosolids in suspension or to facilitate resuspension from the tank bottom, even with low current velocity or a mean velocity of zero.

Fish activity has been studied using several different methods, such as acoustic telemetry (Bégout and Lagardère, 1997; 2004; Schurmann et al., 1998; Bauer and Schlott, 2004), acoustic monitoring (Conti et al., 2006), image processing (Fitzsimmons and Warburton, 1992; Kato et al., 1996), visual observation (Wagner et al., 1995) and infrared sensors (Iigo and Tabata, 1996; Sánchez-Vázquez et al., 1996). However, none of these methods provide a measurable parameter of the turbulence generated by fish swimming activity and all of them have certain restrictions (Table 1.2): most can only be used with a small number of fish, and some are intrusive or subjective methods. Furthermore, fish behaviour, especially in schooling species, may be different when fish are reared at different densities (e.g. rainbow trout (*Oncorhynchus mykiss* L.), Bégout and Lagardère, 2004)), or when a fish is isolated rather than in a group (e.g. mullet (*Mugil cephalus* L.), Fitzsimmons and Warburton, 1992; sea bass (*Dicentrarchus labrax* L.), Bégout and Lagardère, 1997; Bégout et al., 1997).

It would very useful to develop a method for studying fish swimming movements and behaviour in more natural conditions. This could be done using new and innovative techniques and technologies (Peake and MacKinlay, 2004). The method should provide a measurable turbulence parameter and should be suitable for use with high densities to quantify the effect of fish swimming activity on hydrodynamics and on the sedimentation and resuspension of biosolids in aquaculture tanks.

Table 1.2: Techniques used to study fish activity and their pros and cons.

	Pros	Cons	Turbulence measurement?
Acoustic telemetry	-Describes fish path -Velocity is known	-Only with a low number of fish -Problems with tagging small fish or flatfish	NO
Acoustic monitoring	-Determines fish density and behaviour -No fish handling	-Only with a low number of fish	NO
Image processing	-Describes fish path -Velocity is known	-Only with a low number of fish -Problems with flatfish overlapping	NO
Visual observation	-No technology needed -No fish handling	-Subjective -Only with a low number of fish	NO
Infrared sensors	-No fish handling	-Poor information obtained -Only with a low number of fish	NO

1.3. SEDIMENTATION AND RESUSPENSION OF AQUACULTURE BIOSOLID WASTES

Aquaculture sediments in rearing tanks are mainly organic. They are commonly defined as biosolids, which include faeces and non-ingested feed. When biosolids accumulate on the tank bottom, they can promote the spreading of pathogens and the degradation of water quality due to oxygen consumption. In addition, when the biosolids dissolve or leach into the water, they increase the concentration of nitrogenous compounds, which can affect fish growth and welfare. Some biosolids are removed immediately from rearing areas by the water current, but others settle on the tank bottom and need to be resuspended before they can be removed.

The following sections discuss the forces that affect the resuspension of solid particles in a tank. They also describe the characteristics of biosolids and the different techniques for studying resuspension and sedimentation processes in cohesive sediment dynamics.

1.3.1. Characterisation of settleable aquaculture wastes

Sediment classifications can be based on various characteristics, such as particle size, colour, texture and organic content.

Sediments are classified as cohesive (mainly organic) material or non-cohesive (mainly mineral) material depending on their organic content. Mineral sediment transport has been widely studied (Raudkivi, 1990; Van Rijn, 1993; 2005; Chanson, 1999), but cohesive sediments are more difficult to characterise because their properties can change over the time (due to aggregation and disaggregation).

Physical characterisations of sediments are usually based on particle size, specific gravity and sedimentation rate. Sediment size and specific gravity can be determined easily for mineral particles using different techniques (sieves, laser, image analysis, etc.). However, organic materials such as aquaculture biosolids are more difficult to characterise because of three main properties that differentiate them from marine and river sediments: high proportion of organic components, low specific gravity and high cohesiveness. High cohesiveness promotes aggregation, but the particle aggregates are very easy to disrupt and can change their physical characteristics over time, which makes it more difficult to study the dynamics of biosolids. In addition, biosolids can consolidate if they are left undisturbed on the tank bottom (Mehta et al., 1989; Zreik et al., 1998; Orlins and Gulliver, 2003).

When collecting biosolids prior to characterisation, it is important to ensure that their physical properties are not disturbed. Several collection methods can be used: manual stripping (massage of the ventral abdominal wall after fish have been anesthetised) (Chen et al., 1999; Wong and Piedrahita, 2000), dissection of the intestine (Chen et al., 1999), hand-net collection (Chen et al., 2003), traps under cages (Magill et al., 2006) and direct collection from quiescent zones (Merino et al., 2007a).

The properties of aquaculture biosolids have been widely studied, mainly by determining the sedimentation rate (Chen et al., 1999; Wong and Piedrahita, 2000; Chen et al., 2003) and particle size (Chen et al., 1993; Brinker et al., 2005). However, aquaculture biosolids vary considerably according to fish species (Magill et al., 2006), fish diet (Merino et al., 2007b), and the feeding strategies adopted (Cho and Bureau, 2001). It is very difficult to define universal characteristics. Tables 1.3 and 1.4 summarise the physical characteristics of aquaculture biosolids obtained from fish of different species and sizes.

Table 1.3: Specific gravity of biosolids in aquaculture facilities.

Species	Specific gravity	Collection method/location	Source
Brook trout (approx. 50 g)	1.190	Bottom of screen (outside tank)	Chen et al. (1993)
Atlantic salmon smolts (weight and length not given)	1.050-1.153	Near the drain	Patterson et al. (2003)
Rainbow trout (500-800 g; 35 cm)	1.250	Weir overflow (outside tank)	True et al. (2004)

Table 1.4: Sedimentation rate and particle size of biosolids in aquaculture facilities.

Species	Velocity of sedimentation (cm s^{-1})	Particle size (μm)	Collection method/location	Source
Tilapia (weight not given)	1.7-4.3		Radial flow clarifier	Timmons et al. (2001)
Rainbow trout (110-150 g)	1.7		Manual stripping	Wong and Piedrahita (2000)
Atlantic salmon (664±77-1709±259 g)	3.7-9.2		Immediately after defecation, by hand-net	Chen et al. (2003)
Rainbow trout (500-800 g; 35 cm)	0.16	<814	Weir overflow (outside tank)	True et al. (2004)
	2.31	>814		
Rainbow trout (164-499.6 g)	0.0274	88-104	Siphoning at tank bottom	Johnson and Chen (2005)
Sea bream (60-380 g)	0.48 (0.05-3.94)	710	Traps	Magill et al. (2006)
Sea bass (50-280 g)	0.70 (0.10-6.27)	1120		
California halibut (0.17-108 g)	1.7-4.4		Quiescent zone	Merino et al. (2007a)

Recent studies have focused on the inclusion of binders in feed formulations (Brinker et al., 2005; Brinker, 2007) to prevent faeces disintegration, which can promote leaching (Stewart et al., 2006).

1.3.2. Basics of sediment transport

Sediment resuspension in natural systems is driven by bed shear stress τ (the force exerted per unit area parallel to a bed). The shear stress τ of the flow is the force that lifts particles from the bed and entrains them in the flow. If the bed shear stress exceeds a threshold value for a particular particle size and composition (critical shear stress τ_c), the particle will be lifted from the bed and carried by the flow. When the bed shear stress drops below the threshold value, the entrained particle will drop back to the bed. Consequently, the bed shear stress determines whether resuspension or sedimentation occurs. Shear stress is observed in both laminar and turbulent flows.

The molecule path is parallel in laminar flow, and lower velocities are observed close to the solid boundary due to friction (Figure 1.4). The velocity gradient produces the shear stress (Equation 1.9). Shear stress in laminar flows is caused by water viscosity, so it is commonly referred to as viscous shear stress (τ_μ).

$$\tau_\mu = \frac{du}{dh}\mu \qquad \textbf{Equation 1.9}$$

where du is the flow velocity gradient (m s^{-1}), dh is the water depth (m) and μ is the fluid dynamic viscosity (kg m^{-1} s^{-1}).

The magnitude of the shear stress in laminar flows is determined by the velocity gradient (du/dh) (Figure 1.4).

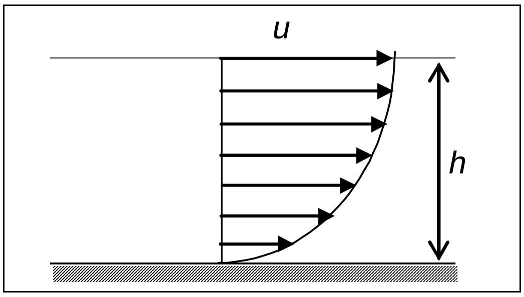

Figure 1.4: Shear stress in laminar flow.

In turbulent flow, molecules move horizontally and vertically and generate continuous mixing (a stochastic process in which the velocities fluctuate in space and time). The instantaneous velocity components in the x-axis in turbulent flows can be defined as:

$$U = u + u' \qquad \textbf{Equation 1.10}$$

where U is the instantaneous velocity, u is the time-average velocity and u' represents the instantaneous velocity fluctuations.

Transfer of movement up and down is done by macroscale processes. Movements of molecules cause a continuous exchange of momentum from one portion of fluid to another. This momentum exchange generates the turbulent shear stress (τ_t) or Reynold stress (Equation 1.11):

$$\tau_t = -\rho\overline{u'w'}$$ **Equation 1.11**

where ρ is the fluid density (kg m^{-3}), *u'* represents the instantaneous velocity fluctuations in the x-axis (m s^{-1}) and *w'* represents the instantaneous velocity fluctuations in the z-axis (m s^{-1}).

Equation 1.11 can be used to calculate the turbulent shear stress, but the total shear stress (τ_T) in turbulent flows is defined as the sum of the viscous and turbulent shear stresses and is expressed as:

$$\tau_T = \tau_\mu + \tau_t = \frac{du}{dh}\mu + \frac{du}{dh}\eta$$ **Equation 1.12**

where η is the apparent or eddy viscosity (kg m^{-1} s^{-1}).

In aquaculture tanks, the bed shear stress generated by circulating water can combine with the free shear stress from the inflow water and the free shear stress from fish swimming activity to promote resuspension.

It is interesting to examine how turbulence affects the terminal fall velocity of suspended biosolid particles. There is a great deal of disagreement on this issue, since it is not clear what type of vertical velocity distribution could be defined in natural conditions or whether turbulence increases or reduces the particle fall velocity (Van Rijn, 1993).

1.3.3. Study of biosolid dynamics

To determine rates of sedimentation or resuspension, a shear stress has to be generated and the amount of resuspended or settled material is measured.

Various techniques have been used to measure sediment accumulation in natural environments (Bloesch, 1994; Thomas and Ridd, 2004). These include using optical or acoustic instruments, taking instantaneous multiple-point water samples, and using sediment traps and/or sediments cores. Sediment traps are the most frequently used technique (Flower, 1991; Kozerski, 1994) because they provide an easy way of collecting particles, although they can overestimate the volume of resuspended sediment if the design is poor (i.e. if the traps do not have an appropriate depth/diameter ratio).

Methods based on annular flumes or tanks (Nowell et al., 1981; Portela and Reis, 2004; Droppo et al., 2007; Neumeier et al., 2007; Traynum and Styles, 2007) were used to study sediment resuspension in the laboratory experiments after collection. These methods produced horizontally and vertically sheared Couette flows. In Couette flows, the shear stress is constant and generated by the laminar flow of a viscous liquid in the space between two parallel plates, one of which is moving relative to the other.

Oscillating grids can also be used to determine resuspension. These types of grids produce no net flow, but the turbulence generated by the oscillations generates a shear stress that decreases with distance from the grid. The turbulence produced in these types of devices is expressed as the root mean square (*RMS*) of the velocity. *RMS* is a statistical measure of the velocity fluctuation (Equation 1.13):

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} \left(v_i - v_{ave}\right)^2}{n}}$$ **Equation 1.13**

where v_i is the instantaneous velocity measurement, v_{ave} is the mean velocity of the flow and n is the number of instantaneous velocity measurements. RMS is expressed in velocity units.

Aquaculture tanks can contain dead zones in which the mean flow is zero. However, even in these cases, a free shear flow induced by fish activity could be sufficient to resuspend biosolids.

Oscillating grids can provide extremely useful information about the turbulence needed to resuspend aquaculture biosolids, which are highly cohesive. To define the self-cleaning conditions of a tank and develop strategies for keeping tanks clean, it is useful to know the turbulence needed to maintain biosolids suspended in the water column, the turbulence needed to resuspend those biosolids that have settled, and the turbulence generated by fish swimming activity.

1.4. OBJECTIVES

1.4.1. General objective

The main goal of this dissertation was to determine design criteria for aquaculture tanks that would produce optimal rearing conditions, ensure that biosolids are removed rapidly, and optimise the use of space and water. The dissertation covers tank hydrodynamics, fish activity and biosolid sedimentation dynamics and highlights the relationship between them (Figure 1.5).

We assessed the effect of flow pattern and fish swimming activity on the hydrodynamic conditions of aquaculture tanks and studied environmental homogeneity and sedimentation processes.

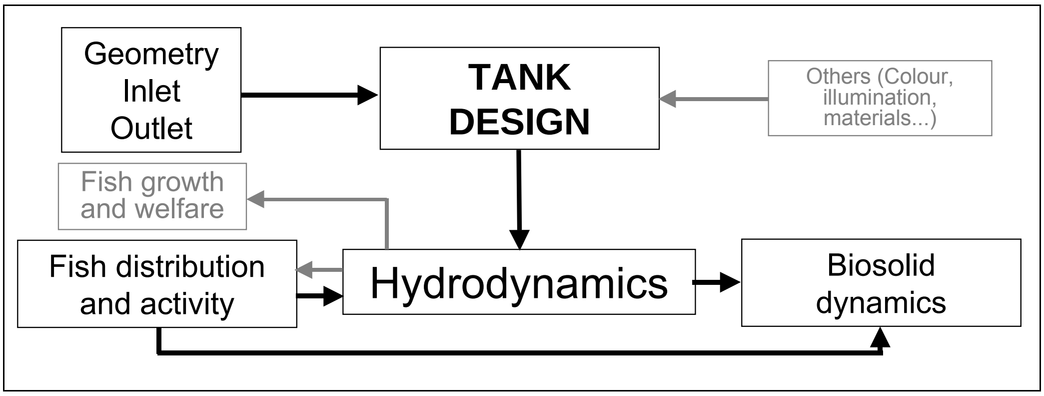

Figure 1.5: Variables involved in tank design and relationships between hydrodynamics, fish activity and biosolid dynamics.

The tank geometry and water inlet and outlet characteristics determine the hydrodynamics in the absence of fish. The tank hydrodynamics affect the rearing environment and fish behaviour. Fish distribution and activity in the tank also affect the hydrodynamic conditions; mixing and resuspension of biosolids increase when pelagic fish are present.

1.4.2. Specific objectives of the articles in this dissertation

- The influence of the geometry and water inlet devices on the flow pattern of the most common aquaculture tanks will be analysed to define design criteria that will improve the rearing conditions and optimise the use of water (Article 1).

  Oca, J., **Masaló I.**, Reig, L. (2004) *Comparative analysis of flow patterns in aquaculture rectangular tanks with different water inlet characteristics.* Aquaculture Engineering 31 (3-4), pp. 221-236

- Design criteria will be established for ‘rotating-cell rectangular aquaculture tanks’, which combine the advantages of rectangular and circular tanks (Article 2).

  Oca, J., **Masaló, I.** (2007) *Design criteria for rotating flow cells in rectangular aquaculture tanks.* Aquacultural Engineering 36 (1), pp. 36-44

- A method for studying fish activity by measuring the turbulence generated by swimming will be developed. This will provide a means of analysing the relationship between the turbulence produced by fish swimming activity and the rearing conditions in the tank (Article 3).

  Masaló, I., Reig, L., Oca, J. (2008) *Study of fish swimming activity using Acoustical Doppler Velocimetry (ADV) techniques.* Aquacultural Engineering 38 (1), pp 43-51

- The turbulence needed to resuspend aquaculture biosolids and to keep them suspended in the water column will be analysed using a vertically oscillating grid adapted to the specific characteristics of aquaculture biosolids (Article 4).

  Masaló, I., Guadayol, O., Peters, F., Oca, J. (2008) *Analysis of sedimentation and resuspension processes of aquaculture biosolids using an oscillating grid.* Aquacultural Engineering 38 (2), pp 135-144

2. PUBLISHED ARTICLES INCLUDED IN THIS DISSERTATION

2.1. Oca, J., **Masaló I.**, Reig, L. (2004) *Comparative analysis of flow patterns in aquaculture rectangular tanks with different water inlet characteristics.*

Aquaculture Engineering 31 (3-4), pp. 221-236.

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Comparative analysis of flow patterns in aquaculture rectangular tanks with different water inlet characteristics

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Abstract

The objective of the work is to improve the design rules of rectangular aquaculture tanks in order to achieve better culture conditions and improve water use efficiency. Particle tracking velocimetry techniques (PTV) are used to evaluate the flow pattern in the tanks. PTV is a non-intrusive experimental method for investigating fluid flows using tracer particles and measuring a full velocity field in a slice of flow. It is useful for analysing the effect of tank geometries and water inlet and outlet emplacements. Different water entry configurations were compared, including single and multiple waterfalls and centred and tangential submerged entries.

The appearance of dead volumes is especially important in configurations with a single entry. Configuration with a single waterfall entry shows a zone of intense mixing around the inlet occupying a semicircular area with a radius around 2.5 times the water depth. A centred submerged entry generates a poor mixing of entering and remaining water, promoting the existence of short-circuiting streams. When multiple waterfalls are used, the distance between them is shown to have a strong influence on the uniformity of the velocity field, increasing noticeably when the distance between inlets is reduced from 3.8 to 2.5 times the water depth. The average velocities in configurations with multiple waterfalls are very low outside the entrance area, facilitating the sedimentation of biosolids (faeces and non-ingested feed) on the tank bottom. The horizontal tangential inlet allows the achievement of higher and more uniform velocities in the tank, making it easy to prevent the sedimentation of biosolids.

Keywords: Particle tracking velocimetry; Aquaculture tank design; Flow pattern

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1. Introduction

The design of tanks in inland aquaculture systems is an essential issue in order to achieve optimal conditions for fish and minimise waste discharge into the environment, and has been dealt with by different authors (among others Wheaton, 1977; Cripps and Poxton, 1992, 1993; Lawson, 1995; Ross et al., 1995; Timmons et al., 1998; Watten et al., 2000). A comprehensive approach to the tank design should include the geometry and the water inlet and outlet characteristics, which together will determine the flow pattern.

Two types of geometry are used in the construction of aquaculture tanks: circular and rectangular.

Circular tanks are frequently self-cleaning. The circular flow pattern moves biosolids (non-ingested feed and faeces) to the central outlet, where they are swept out in the outlet current. A downstream settling zone is required to collect biosolids from these ponds. Environmental conditions are usually very uniform in this kind of tank due to the effective mixing of water achieved (Timmons et al., 1998).

In rectangular tanks, flow pattern is much more unpredictable, heavily depending on the tank geometry and the characteristics of water inlets. In this kind of tank the majority of biosolid particles usually settle on the bottom, especially at low fish densities, when the turbulence produced by fish movement is not very great. In rectangular tanks it is also much more usual to find heterogeneous culture environments caused by the lack of mixing uniformity, which generates dead and by-passing volumes. These conditions will provoke disparity in fish distribution and fish quality and in some cases an increase in aggressive behaviour of fish (Ross et al., 1995).

Despite the number of problems above described, rectangular tanks are widely used in aquaculture farms on account of the fact that they are easier to construct, facilitate fish handling and adapt to usual plot geometries. The water inlet is usually made through submerged horizontal inlets or through waterfalls placed in one extreme of the tank. The influence of inlet and outlet arrangements in the hydraulic behaviour of the tanks has been widely studied in circular tanks (Klapsis and Burley, 1984; Tvinnereim and Skybakmoen, 1989; Timmons et al., 1998) but scarcely in rectangular tanks. Some authors have suggested inlet configurations placed along the sidewalls of the rectangular tanks to increase the mixing flow conditions and provide self-cleaning proprieties (Watten and Beck, 1987; Watten et al., 2000).

In general, two ideal flows can be defined for rectangular tanks: the “plug flow” and the “mixing flow”. In the “plug flow” there is no mixing or diffusion along the flow path and the maximal waste concentration is found in the outlet. In the “mixing flow” the exit stream from the tank has the same composition as the fluid within the tank (Levenspiel, 1979), providing greater uniformity conditions due to the intense mixing. Nevertheless, in rectangular aquaculture tanks it is very usual to have deviations from these two ideal flow patterns, existing short-circuiting streams leaving the tank without mixing well with remaining water, and dead volumes with low renovation rates. Both phenomena will contribute to a low efficiency in water use and to make the treatment of wastes more difficult.

Many authors have evaluated the hydraulic behaviour of some aquaculture tanks using methods like the analysis of residence time distribution (RTD) (Burley and Klapsis, 1985; Watten and Beck, 1987; Watten and Johnson, 1990; Cripps and Poxton, 1993; Watten et al., 2000) or tracer tests (Burrows and Chenoweth, 1955; Tvinnereim and Skybakmoen, 1989). These evaluations are based on the temporal evolution of a measurement that is a consequence of the flow pattern (concentration of a tracer), but none of them provide a quantitative description of the flow pattern. As a consequence, these methods are useful for the evaluation of existing tanks, measuring the mixing intensity and detecting flow anomalies like short-circuiting or dead volumes, but not to give useful information for improvement of the tank design.

The direct measurement of velocities at various points of the tank volume has also been used by some authors (Burley and Klapsis, 1985; Watten et al., 2000) but the number of measurements is necessarily small and the flow is inevitably disturbed by the presence of the measuring probe.

In the last decade, the experimental methods for characterising flow patterns have improved greatly due to availability and the increase in computer power, which has allowed the development of particle velocimetry techniques. These methods use tracer particles and measure a full velocity field in a two-dimensional slice of a flow. One of these techniques, called “particle tracking velocimetry” (PTV), utilises time series of images, estimates the position of the particles and measures their displacement. It has been used in many works in order to characterise flow patterns in the field of building ventilation (Montero et al., 2001), river engineering (Uijttewaal, 1999) and marine engineering (Sveen et al., 1998; Grue et al., 1999; Chang et al., 2002). Results are usually presented as a vectors map where the length of every arrow is proportional to the velocity.

The application of PTV to other fields, such as the design of aquaculture tanks, could provide useful information in order to improve the design rules, thus aiding the achievement of better culture conditions and water use efficiency.

Taking advantage of PTV techniques, the goal of this work has been the evaluation of the flow pattern obtained in rectangular tanks, to analyse the effect of geometrical characteristics and inlet and outlet emplacement.

2. Material and methods

2.1. Flow visualisation

The experiments were carried out using a rectangular tank made of transparent methacrylate, 100 cm long and 40 cm wide. The water depth was always close to 5 cm. Exchangeable gates placed in the tank extremes allowed the water inlet and outlet characteristics to be changed easily. The circulation of water was achieved using a volumetric pump equipped with a variable speed motor, in order to adjust the recirculation flow rates (Fig. 1).

The water volume was “seeded” with small particles of pliolite (Eliokem, pliolite S5E), a granular material with good reflective properties and density approximately 1.05 g cm^{-3}. The particles used passed through a US Standard Sieve #18 screen (1.00 mm) but were retained on a #35 screen (0.50 mm). The used amount of dry pliolite was around 1 g l^{-1}. In order to give neutral buoyancy to these particles, they must be submerged in a wetting agent to reduce the surface tension and sodium chloride must be added to the water tank (around 65 g l^{-1}) to equal water and pliolite densities.

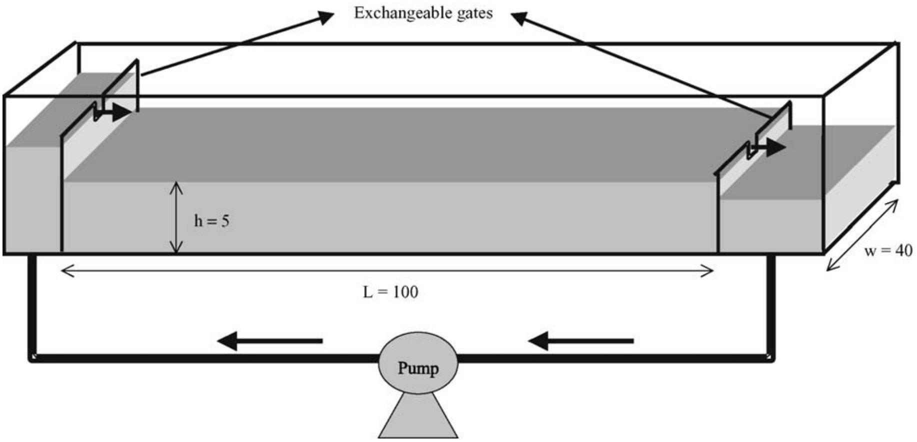

Fig. 1. Recirculating water system and dimensions of the tank.

The following step is to illuminate a slice of flow (around 5 mm thick) in the section where the velocity field has to be obtained. Some vertical and horizontal sections were analysed in each experiment for a better understanding of the three-dimensional pattern. Following the pliolite particles from this slice during a short time period, the bi-dimensional velocity field in the lighted slice can be found.

In order to achieve a sufficiently good resolution of the images, the tank analysis was divided into two halves, analysing separately the half closer to the inlet and the half closer to the outlet. The analysis of both halves was made at different times, that is why, when the flow pattern is time dependant, the flow pattern of the first half may not fit the flow pattern in the second half.

2.2. Particle tracking and analysis

In order to track particles, the images of the flow must be captured, the particles must be located within these images, and the relationship between particles in successive images must be determined.

The illuminated region of the flow was recorded on a Super VHS videotape using a monochrome CCD video-camera (COHU 4912). To track the particles, the videotape was replayed and the images were captured by digitising the video using a frame grabber card (Data Translation 2861). The control of the video recorder (Panasonic AG-7350) was carried out by the same computer in which the frame grabber card was installed, using a specific software for this application (Digimage). The software defines a particle as an area of an enhanced image satisfying a number of criteria, based on the intensity, size and shape of the particles. Once all the particles in an image have been found, they need to be related back to the previous image to determine which particle image is which physical particle. The displacement, velocity and trace of each particle are determined from sequences of frames. The summarisation of the data obtained is made by using an analysis package (Trk2DVel), which provides the results in the form of graphical output or statistics of the flow (Dalziel, 1999).

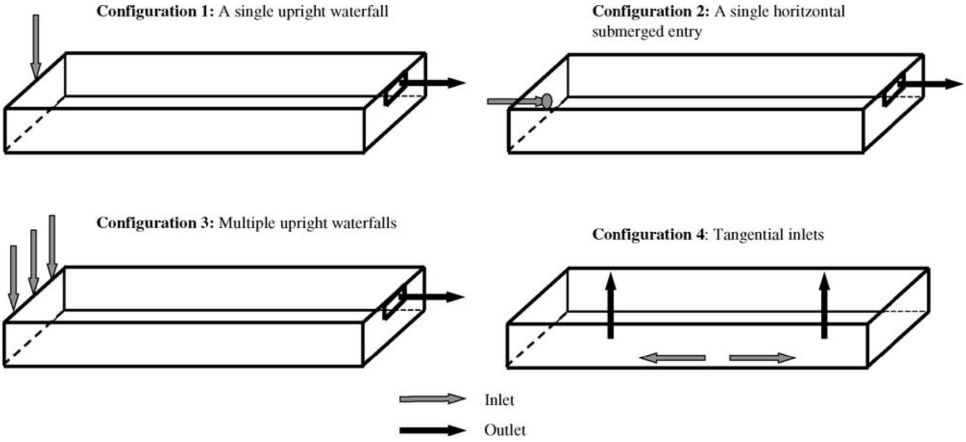

Fig. 2. Tank configurations analysed.

2.3. *Tank configurations analysed*

The tank configurations analysed are presented in Fig. 2.

1. A single upright waterfall (centred in one of the shorter walls of the tank).
2. A single horizontal submerged entry (centred in one of the shorter walls of the tank).
3. Multiple upright waterfalls (uniformly distributed in one of the shorter walls of the tank).
4. Tangential inlets placed in the centre of the longer side wall, in order to perform two large eddies.

The outlets were always placed superficially in the centre of the opposite wall of the entry, except for configuration 4, where the outlets are placed in the centre of the eddies, at the tank bottom.

Three different flow rates were used in configuration 1 in order to study the influence of the flow rate in the flow pattern observed around the waterfall.

In configuration 3, two and three inlets uniformly distributed were studied, corresponding to a distance between inlets of 3.8 and 2.5 times the depth, respectively.

The different flow rates used with every configuration can be seen in Table 1, together with the water depth and the exact emplacement and characteristics of the inlet.

To transfer the results to other geometrically similar tanks, the main criteria to be used will be the Froude number ($Fr = v/(gL)^{1/2}$), which relates inertial forces to gravity forces and the Reynolds number ($Re = Lv/\nu$), which relates inertial forces to viscous forces. If the same fluid (i.e. water) is used in both the model and the full-scale prototype it is not possible to keep both the Froude and Reynolds numbers in the model and full-scale. In free-surface flows gravity effects are dominant, and model-prototype similarity is usually performed with the Froude number, neglecting the effect of viscous forces.

To have the same Froude number in two geometrically similar tanks with a length scale λ_L, the velocity scale (λ_v) must be $\lambda_v = \lambda_L^{0.5}$, the flow rate scale ($\lambda_f$) $\lambda_f = \lambda_L^{2.5}$, and the exchange rate scale λ_e must be $\lambda_e = \lambda_L^{-0.5}$. Thus, an exchange rate 9 h^{-1} in the analysed

Table 1
Flow rate, exchange rate and water depth in analysed configurations

	Distance between inlets/water depth	Flow rate ($1\,h^{-1}$)	Water depth (cm)	Velocity inlet ($cm\,s^{-1}$)	Exchange rate (h^{-1})	Fall height (cm)
Horizontal entry	–	100	5.0	13.8	5.0	–
Single waterfall	–	95	5.3	–	4.5	
	–	140	5.4	–	6.5	3
	–	182	5.5	–	9.1	
Multiple waterfalls	3.8 2.5	182	5.5	–	9.1	2.5
Tangential inlets	–	215	6.0	77.5	9.0	–

model would correspond to $2\,h^{-1}$ in a tank 20 times larger (20 m long × 8 m wide). This transfer would provide a good approximation to the flow pattern in the larger tank, but it should be verified through full-scale experiments due to the greater importance of viscous forces in the smaller tanks.

3. Results and discussion

The development of this section starts with a detailed description of the hydraulic aspects for each of the configurations evaluated in the present work. Later, all the configurations will be compared and the possible implications on fish culture discussed.

3.1. Configuration 1: a single upright waterfall

With this configuration a vertical eddy is always formed close to the inlet in the way shown in Figs. 3 and 4.

Fig. 3 shows a vertical section taken in the centre of the longitudinal axis of the tank, near the inlet, and two horizontal sections taken close to the free surface (A) and close to the tank bottom (B). In the vertical section, the vertical vectors corresponding to the entry waterfall are not plotted because they are out of range of velocity that can be detected by the equipment, but the eddy formed by this vertical flow is clearly shown. In the horizontal sections the velocity vectors are advancing in the bottom section and going back in the top section, creating a semicircular area of intense mixing around the waterfall with a radius equal to the eddy length.

The length of the vertical eddy is not appreciably altered by the flow rate, as can be seen in Fig. 4 where the vertical eddies obtained with the three different flow rates are shown. This length is always close to two and a half times the water depth.

Outside the above defined area of intense mixing, large horizontal eddies are formed along the length of the tank as can be observed in Fig. 5. Each eddy tends to occupy the whole width of the tank, with considerable dead volumes appearing in the eddy cores. Owing to these large eddies, the velocity field is very heterogeneous and the internal recirculation in the tank is very important.

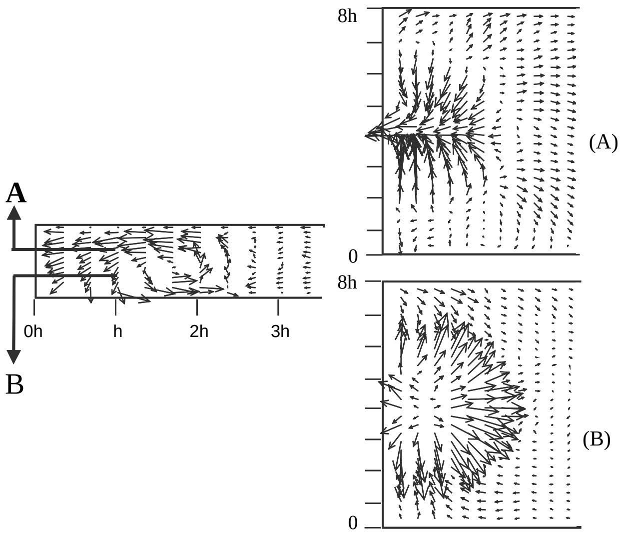

Fig. 3. Velocity fields in a vertical section taken in front the single waterfall (left) and in the two horizontal sections A and B (right).

Fig. 6 shows a sequence of pictures with the flow patterns observed for 2 min, averaging 20 s in every picture. The great time dependence of the flow patterns observed with this kind of configuration must be highlighted. Eddies are continuously changing their shape and emplacement.

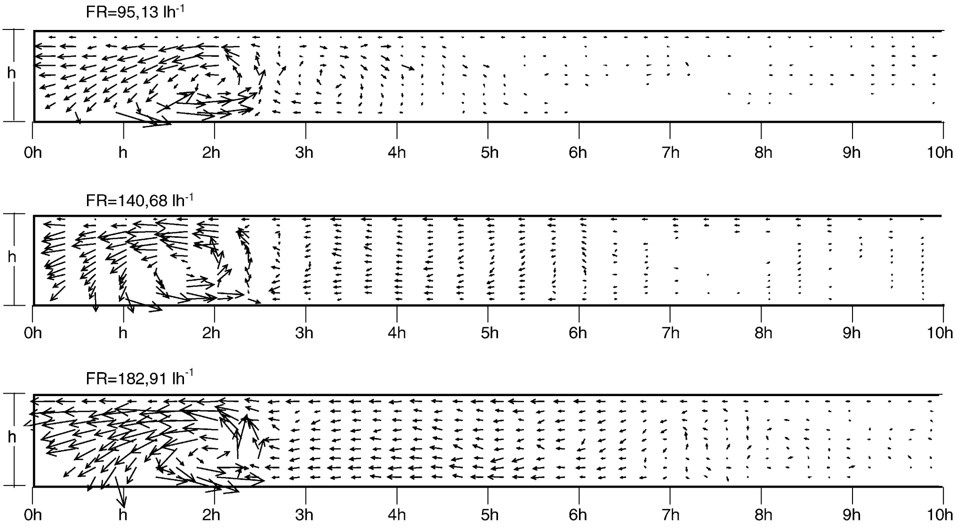

Fig. 4. Velocity fields in vertical sections of the first half of the tank with configuration 1, using different flow rates.

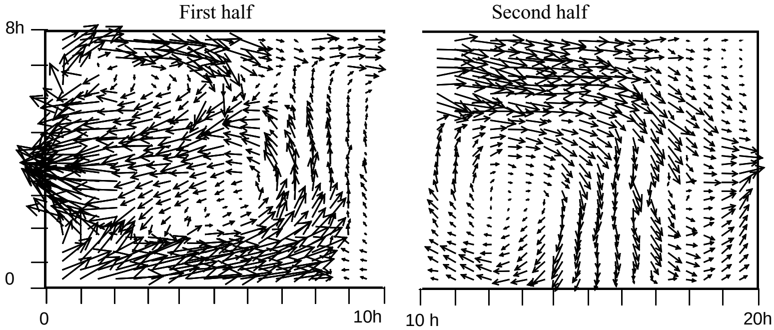

Fig. 5. Velocity fields in horizontal sections with configuration 1.

3.2. Configuration 2: a single horizontal submerged entry

The field of velocities in a horizontal section of the tank with this configuration is shown in Fig. 7. It can be seen that the plume formed by the entering water maintained its symmetry along the first quarter of the tank, which means along a length around five times the water depth. From this distance to 10 times the water depth the symmetry is progressively lost. At both sides of the plume, lateral eddies can be observed. In the second half of the tank, the flow symmetry is lost and a big horizontal eddy is formed occupying most of the second half of the tank. The shape of this horizontal eddy also changes with time. Considerable dead volumes are observed in the centre of eddies and a great internal recirculation of water must

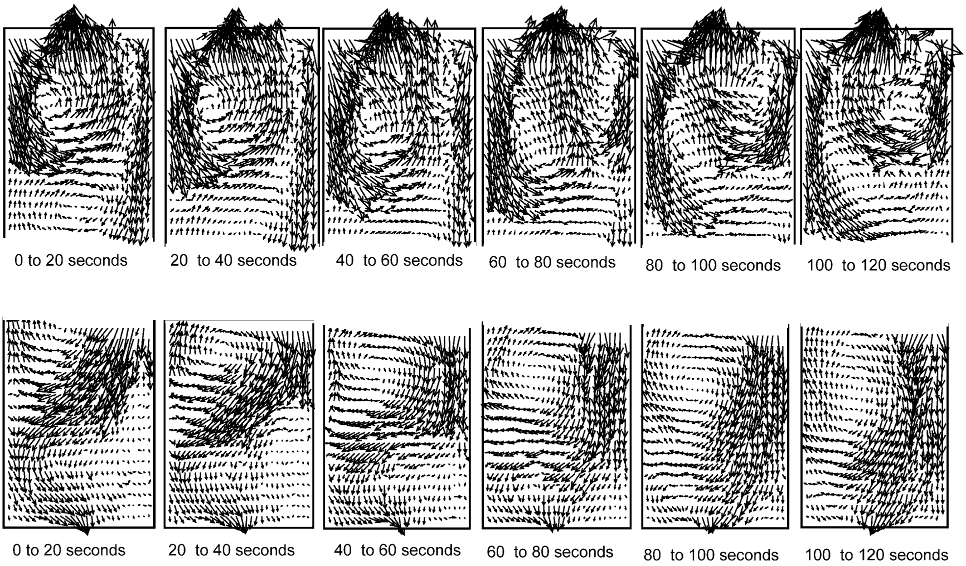

Fig. 6. Sequence of flow pattern observed along 2 min with configuration 1.

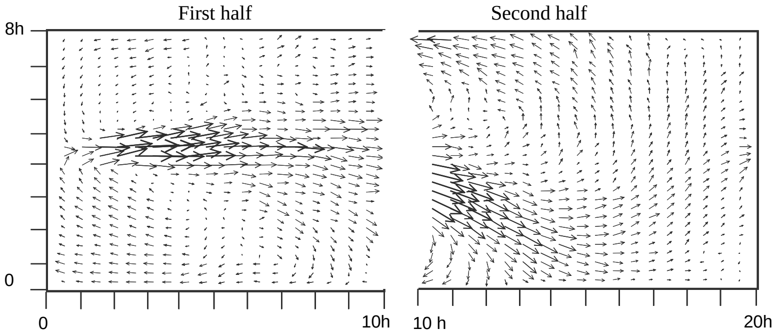

Fig. 7. Velocity fields in horizontal sections with configuration 2.

be assumed. The flow pattern obtained is in accordance with the results obtained by Stovin and Saul (1994) using a propeller meter in a sedimentation tank with similar geometrical and inlet characteristics.

The observed flow pattern also suggests the existence of an important short-circuit stream, resulting from the absence of an area of intense mixing between the entering water and the stored water. The short-circuit stream will not only increase the heterogeneity of environmental conditions inside the tank, but will also contribute to having low water use efficiency in open systems and will make water treatment in recirculating systems more difficult.

Despite the described drawbacks with this kind of configuration, it is still very usual to find it in some inland grow-out marine fish farms.

3.3. Configuration 3: multiple upright waterfalls

Two trials are evaluated in this configuration. The first with two waterfalls and the second with three waterfalls. The distance between waterfalls is, respectively, 3.8 and 2.5 times the water depth. Fig. 8 shows the flow pattern in two horizontal sections for each trial, one of them taken close to the free surface (top section) and the other close to the bottom (bottom section). Considering the results of configuration 1, where the eddy radius was always close to two and a half times the water depth, the analysed distances between inlets mean an overlapping of the expected single eddies around 50 and 100%, respectively.

Observing the same figure, the effect of overlapping eddies in the flow pattern can be easily seen. In the top section, a horizontal plume is formed midway between two eddies. Meanwhile, in the bottom section, the flow in front of the waterfall seems to be mainly going back and the velocities perpendicular to the main flow direction seem to be higher when compared with the single waterfall configuration. A better understanding of this behaviour can be obtained by observing, in Fig. 9, two vertical sections placed midway between two entries (A) and in front of a water entry (B). In the first, most of the vectors are advancing and rising, forming the superficial plume. Meanwhile, in the second, most of the vectors are going back and down. This behaviour suggests that vertical eddies are formed in the direction perpendicular to the tank length, as shown in Fig. 10. These eddies will contribute to a better mixing of fluid in the first part of the tank and to a larger dissipation of the kinetic energy in this first part.

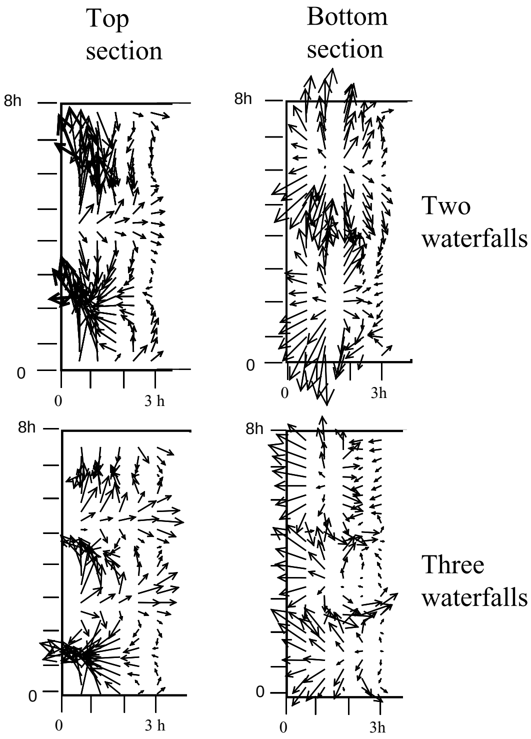

Fig. 8. Velocity fields in horizontal sections taken close to the inlet in configuration 3, with two and three waterfalls.

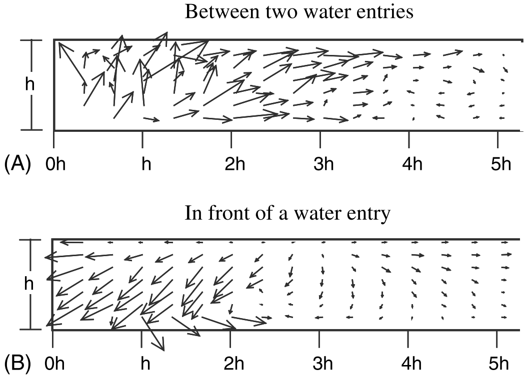

Fig. 9. Velocity fields in vertical sections in configuration 3. The first taken (A) between two water entries and (B) the second in front of water entry.

Fig. 11 shows that after the “mixing volume” produced in the entry, the observed flow is much more uniform in this kind of configuration than with the previous one, preventing the formation of large horizontal eddies and, therefore, the internal recirculation inside the tank.

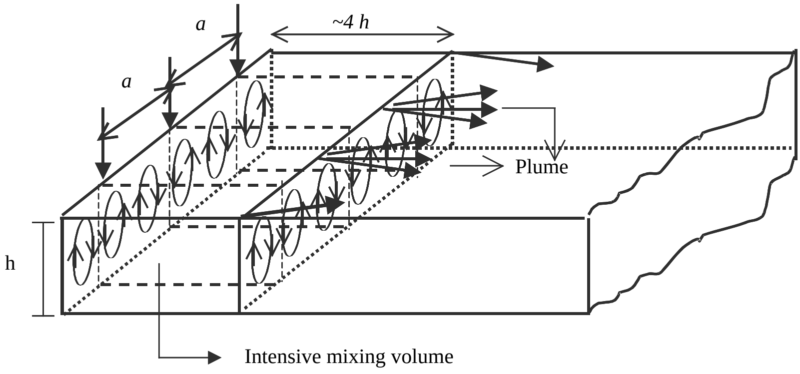

Fig. 10. Flow behaviour in a configuration with multiple waterfalls when the distance between eddies is around 2.5 times the water depth.

When comparing the flow pattern with two and three waterfalls, the main difference is the homogeneity in the velocity field. In the tank with two entries (distance 3.8 times water depth) the circulation at one of the tank sides is much higher than at the other side, while with three waterfalls (distance 2.5 times water depth) the velocity field is more homogeneous, allowing more uniform culture conditions and a more efficient use of water.

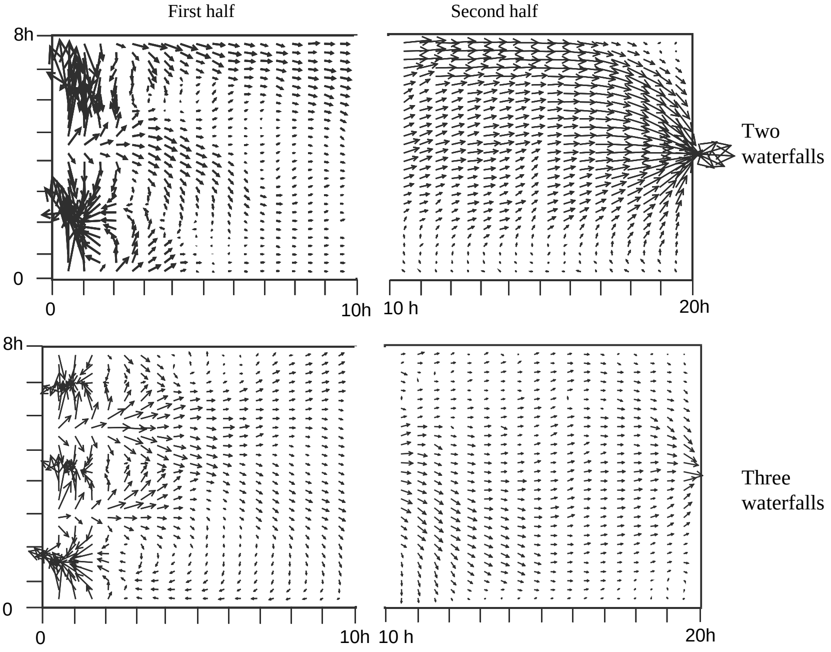

Fig. 11. Field velocities in horizontal sections of configuration 3 with two and three waterfalls.

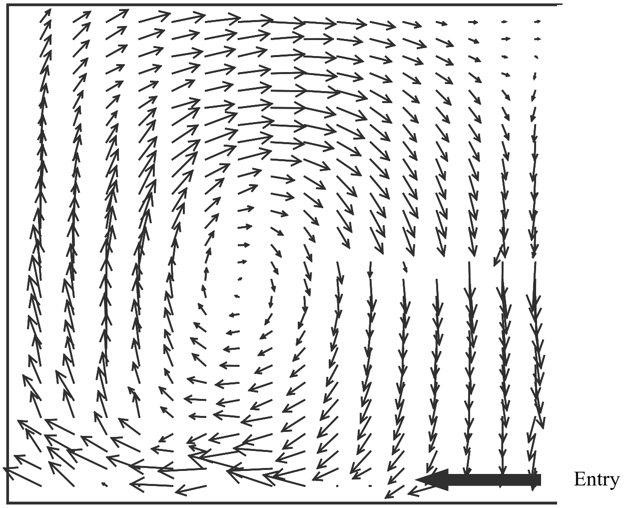

Fig. 12. Field velocities in a horizontal section of one of the tank halves with configuration 4.

3.4. Configuration 4: tangential inlets placed in the centre of the longer side wall

This kind of configuration is made in order to force the formation of large eddies occupying the whole tank width. The outlets are placed in the centre of these eddies in a similar way to those in the mixed-cell rearing unit described by Watten et al. (2000). This can provide some of the advantages of the circular tanks described in Section 1 (uniformity and self-cleaning) while maintaining the operating advantages of rectangular tanks. The analysed configuration is probably the simplest way to induce this flow pattern with the minimal number of water inlets. In Fig. 12 we can see a single eddy occupying a half of the whole tank volume. The eddy shape was slightly elliptical, the largest diameter being 1.25 times the shortest. The time-stability of the flow pattern obtained, together with the absence of relevant vertical gradient of velocities, must be highlighted.

One of the advantages of this configuration is the higher velocities achieved, preventing the biosolids from settling on the tank bottom. The ratio between the average measured velocity in the horizontal section (v_{avg}) and the expected average velocity assuming plug flow conditions (v_{pf}: recirculation flow rate divided by water depth and tank width), will give a measure of the velocity increase obtained with this configuration. In the present case, the measured average velocity in the horizontal section was $2.88\,\mathrm{cm\,s^{-1}}$, which is around 12 times the plug flow velocity, much higher than those obtained with the previous configurations.

The ratio between the average velocity and the inlet jet velocity in this experiment was 0.037, lower than the 0.2 reported for circular tank designs (Skybakmoen, 1989), but very close to the percent obtained by Watten et al. (2000) in a rectangular tank with six horizontal eddies with a diameter about six times larger. These ratios can be increased optimising the water inlet velocity and the number and emplacement of the water inlets, or modifying slightly the tank geometry. This matter is the object of an ongoing new work.

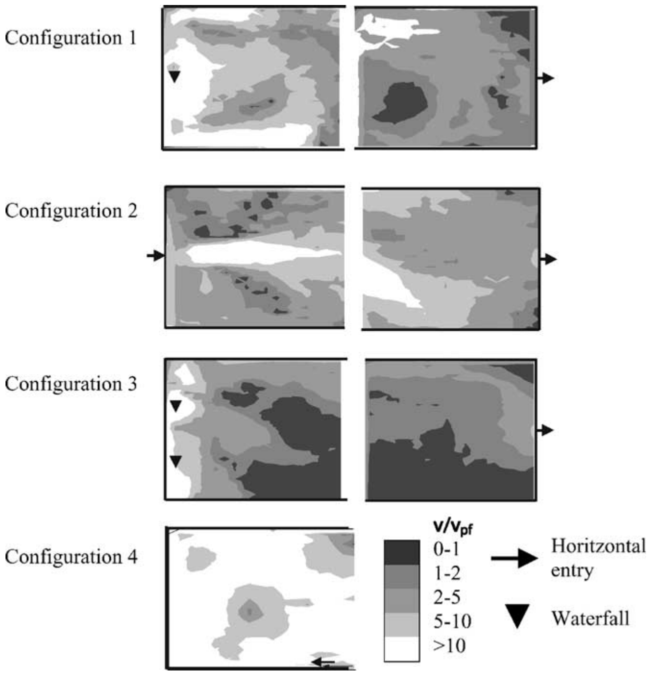

Fig. 13. Spatial distribution of the non-dimensional velocity (v/v_{pf}) in the horizontal section of the four analysed configurations.

3.5. Comparison between configurations

Water velocity is a parameter strongly influencing the performance of a tank for fish culture, through both its self-cleaning function and the fish energy expenditure caused by swimming. To illustrate the differences between the ranges of velocities obtained with all the configurations analysed and their spatial distribution Fig. 13 has been designed. It shows the tank area occupied by the different ranges of velocities in a horizontal section, at a depth of around a 1/4 the water depth. The higher settlement of biosolids is expected in areas with lower velocities. To make the comparison between configurations easier, velocities have been given in a non-dimensional way, relating the velocity at every point with v_{pf} and giving, in all the figures, the distribution of the ratio v/v_{pf} in the horizontal section.

In configuration 4, velocities are higher than 10 times v_{pf} in 70% of the tank area and higher than five times v_{pf} in 94% (Table 2). This means that it is easier to prevent the sedimentation of biosolids inside the tank, a downstream water treatment being necessary to collect them. In this configuration, the swimming performance of fish using this tank could be better than in a typical plug flow tank, considering that forced swimming improves fish growth and disease resistance as cited by Watten et al. (2000). Furthermore, water velocity can be accurately controlled in this tank, and it can be adapted to the requirements of several species, sizes, ages or culture situations.

Table 2
Percentage of the tank area with v/v_{pf} included in the intervals 0–1, 2–5, 5–10 and larger than 10, and average of v/v_{pf} in the whole tank

	v/v_{pf}					v_{avg}/v_{pf}
	0–1	1–2	2–5	5–10	>10	
Configuration 1						
First half	2.18	11.51	27.38	32.94	25.99	7.06
Second half	13.72	34.59	46.92	4.77	0.00	2.25
Whole	7.95	23.05	37.15	18.85	13.00	4.68
Configuration 2						
First half	6.94	19.44	46.23	17.86	9.52	4.55
Second half	1.59	10.71	52.98	27.98	6.75	4.69
Whole	4.27	15.08	49.60	22.92	8.13	4.62
Configuration 3						
First half	33.40	18.69	32.21	10.14	5.57	2.94
Second half	42.06	41.27	16.07	0.60	0.00	1.21
Whole	37.73	29.98	24.14	5.37	2.78	2.08
Configuration 4						
Whole	1.14	1.37	3.42	24.37	69.70	11.76

The second half of the tank in configuration 3 is the closest to the plug flow conditions, with 42% of the area below the v_{pf} and 83% of the area below two times v_{pf}. If the exchange rate or the fish density is not very high, we can expect most of the biosolids to settle inside the tank, having to be collected from the tank bottom, thus providing a very deficient self-cleaning function.

Configurations 1 and 2 give the most heterogeneous distribution of velocities in the tank area, which will also produce a heterogeneous distribution of biosolids on the tank bottom. This sedimentation of biosolids does not exclude their presence in the effluent, due to the existence of internal streams attributable to the horizontal eddies formed all along the tank and also to the great penetration of the inlet plume in configuration 2. The heterogeneity inside the tank would have a direct effect on the use of the tank by fish. The higher the heterogeneity in water quality, the lesser the efficiency of the water use and space by fish. Furthermore, when strong gradients are set in the tank, territorial behaviour takes place, as Ross et al. (1995) demonstrated with rainbow trout maintained in plug-flow tanks, and as a consequence agonistic interactions arose between fish.

4. Conclusions

Particle tracking velocimetry has proved to be a very useful tool for three-dimensional study of the hydrodynamic characteristics of fish production tanks in a quick and inexpensive way. In rectangular tanks, these hydrodynamic characteristics have shown to be dramatically affected by the emplacement of the water inlets and by their geometry, providing big differences in mixing conditions and distribution of velocities inside the tank.

The mixing between entering and remaining water was shown to be very low in configuration 2 (with a single horizontal entry) where considerable short-circuiting streams can be expected. Configurations with single or multiple waterfalls (configurations 1 and 3) showed a zone of intense mixing around the inlet occupying a semicircular area with a radius of around two and a half times the water depth in the single waterfall, and extending the whole tank width when the existence of multiple waterfalls allowed these areas to overlap. In configuration 4, with tangential inlets, the higher velocities obtained in the eddy will contribute to obtaining a good mixing and uniform environmental conditions in the entire tank volume.

The appearance of dead volumes is especially significant in configurations with a single entry (configurations 1 and 2) in the centre of the horizontal eddies formed along the tank area. The emplacement of these dead volumes is mostly unpredictable, due to the time dependence on the flow patterns obtained with these configurations.

Only in the configuration with multiple waterfalls (configuration 3), can the obtained flow pattern be considered to be close to the plug flow conditions, without the presence of horizontal eddies outside the area of intense mixing above described and in the area closer to the outlet. The distance between the inlets was shown to have an appreciable influence on the uniformity of the horizontal velocity field, which increased noticeably when the distance between inlets was reduced from 3.8 to 2.5 times the water depth. This increase in uniformity provides higher efficiency in water use.

The distribution of velocity magnitude inside the tank is much more uniform in configuration 4, which has also the highest average velocities. These characteristics make this kind of configuration the most interesting for the achievement of self-cleaning conditions. Increases in the number of inlet points and modifications in the tank geometry could increase the average velocities, but the tank construction and the fish management could also become more complicated. Further trials are being developed to analyse the effect of some single modifications in the tank geometry using PTV techniques.

Acknowledgements

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Design criteria for rotating flow cells in rectangular aquaculture tanks

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Abstract

This work analyzes the simplest inlet and outlet configurations that create homogeneous rotating flow cells in rectangular aquaculture tanks, in order to combine the advantages of rectangular and circular tanks. All the configurations analyzed had a single jet discharge per rotating flow cell, with the drain placed in the center of each rotating flow cell. Length/width ratios (*L*/*W*) of 0.95, 1.43 and 1.91 were tested. In addition, the effect of placing oblique baffles in the walls to redirect the water currents was assessed. Experiments were conducted in a laboratory-scale tank with a Reynolds number of approximately 6000. Particle tracking velocimetry techniques were used to characterize the flow pattern in a horizontal cross-section at the midpoint of the water depth. A tank resistance coefficient (C_t) was defined in order to characterize the resistance offered by each tank configuration to the circulation of water. Results indicated that when *L*/*W* was increased from 0.95 to 1.43, the main vortex that was formed occupied most of the rotating cell area and did not create significant dead volumes in the tank. A *L*/*W* ratio of 1.91 dramatically reduced flow uniformity and hardly increased C_t values. The presence of baffles contributed to high velocities in the area around the center drains and decreased C_t values by 30–35%. Higher velocities are critical to the self-cleaning properties of the tank. The calculation of a C_t value makes it easier to obtain the desired average velocities in the tank by adjusting the water exchange rate and the water jet discharge velocity.

Keywords: Aquaculture tank design; Rotating flow cells; Baffles; Length/width ratio

1. Introduction

The selection of tank geometry in inland aquaculture systems is essential in order to ensure optimal fish culture conditions, minimal waste discharge into the environment and easier management of fish farms. Two main geometries are used in the construction of aquaculture tanks: rectangular and circular. In general, rectangular tanks are easier to handle and clean than circular tanks. Nevertheless, low velocities and poor mixing of water in rectangular tanks lead to the creation of dead volumes, which in turn cause the accumulation of biosolids (faecal solids and uneaten feed) on the tank bottom. These biosolids increase the biochemical oxygen demand and produce large gradients in dissolved oxygen and fish metabolites, which can create disparities in fish distribution and fish quality (Watten and Beck, 1987).

In circular tanks, water is injected tangentially to achieve higher velocities and create mixing flow conditions (Levenspiel, 1979). This type of flow generates more homogeneous water quality throughout the tank and allows for a more uniform distribution of fish (Ross et al., 1995; Ross and Watten, 1998). Higher

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velocities create self-cleaning conditions by rapidly displacing biosolids to the central outlet (Timmons et al., 1998). Furthermore, dual drain systems can easily be adapted to circular tanks to obtain two separate effluents, one of them removing approximately 5–20% of recirculating water from the center of the tank bottom, but containing 80–90% of the suspended solids (Van Toever, 1997; Lunde et al., 1997; Schei and Skybakmoen, 1998; Summerfelt et al., 2000; Davidson and Summerfelt, 2004). Dual drains simplify water treatment and are particularly suited to recirculating aquaculture systems. Wong and Piedrahita (2003) and Lareau et al. (2004) suggested some equivalent devices for raceways, but these are not widely used on a commercial scale. Another important advantage provided by circular tanks is the possibility of adjusting water velocity to the desired fish swimming speed, which will depend on the species and the size of fish (Woodward and Smith, 1985; Watten and Johnson, 1990; Timmons and Youngs, 1991; Losordo and Westers, 1994).

Several attempts have been made to combine the hydrodynamic advantages of circular tanks and the handling advantages of raceways. Vertical baffles, installed perpendicular to the water flow, increased bottom velocities and reduced biosolid accumulation but interfered with fish handling and in some cases caused behavioral problems (Boersen and Westers, 1986; Kindschi et al., 1991; Wagner, 1993; Barnes et al., 1996; True et al., 2004). In another approach, a pipe placed along the bottom of one side of the raceway jetted water along the tank bottom, thus establishing rotary circulation on the longitudinal axis of the tank. This provided self-cleaning properties (Watten and Beck, 1987; Watten and Johnson, 1990) but the costs of tank construction were high.

One particularly important development was the "rectangular mixed-cell rearing unit" proposed by Watten et al. (2000), in which vortex cells were created within a rectangular raceway by directing four water jets tangentially to each cell, thereby establishing rotary circulation. In addition, drains were placed in the center of each cell, with a distance between outlets equal to the tank width. The mixing flow characteristics of these rectangular tanks were comparable to those observed in circular tanks. Similar flow characteristics were also obtained by Oca et al. (2004) and Masaló and Oca (2004) in a rectangular tank with only one tangential water inlet per cell.

Tvinnereim (1988) and Tvinnereim and Skybakmoen (1989) studied the influence of inlet design and impulse force on the current velocity and flow distribution in circular and octagonal tanks. The circulating velocity and transport capacity of the water for the removal of particles from the tank bottom were controlled by adjusting the impulse force F_i (Eq. (1)) of the inflowing water:

$$F_{\mathrm{i}} = \rho Q(V_2 - V_1) \tag{1}$$

where ρ is the density of water, Q the injected water flow rate and V_1 and V_2 are the mean circulating velocity in the tank and the jet velocity from the inlet, respectively.

The aim of this work was to analyze the simplest inlet and outlet configurations in rectangular aquaculture tanks that create homogeneous rotating flow cells, combining the advantages of both rectangular raceways and circular tanks. Each cell would therefore consist of a large vortex occupying the entire tank width with individual cells aligned on the longitudinal tank axis. Several configurations were tested to evaluate the effect of water discharge jets, the separation of drains and placing oblique baffles in the walls to divert the water currents. The measured velocity magnitudes and uniformities in the rotating flow cells were compared with those obtained in a circular tank.

2. Material and methods

2.1. Tank configurations

Experiments were carried out using a rectangular tank 200 cm long and 35 cm wide. A circular tank with a diameter of 49 cm was used for comparison. Water depth was maintained at approximately 6 cm in both systems. Water was circulated using a pump equipped with a variable speed motor, allowing adjustment of inlet discharge jets rates.

The selected water inlet configuration consisted of a single water jet entry for each rotating cell to ensure simple construction and the possibility of adaptation to existing rectangular tanks. Water jet depths were 3 cm. Drains were located in the center at the bottom of each rotating cell area (Fig. 1).

Three cell length/width ratios (L/W) were analyzed: 0.95, 1.43 and 1.91, corresponding to 6, 4 and 3 vortices for the total tank length. In addition, the effect of oblique baffles that diverted the water currents was evaluated. Three configurations were tested: without baffles, with baffles in one side wall and with baffles in both side walls. The baffles were placed in the midpoint between two opposite water inlets (Fig. 2) at an inclination of 45° with the lateral wall. Baffles were separated by a distance equal to twice their length, allowing them to be turned and aligned with the wall for easier manipulation of fish and permitting longitudinal flow in specific circumstances.

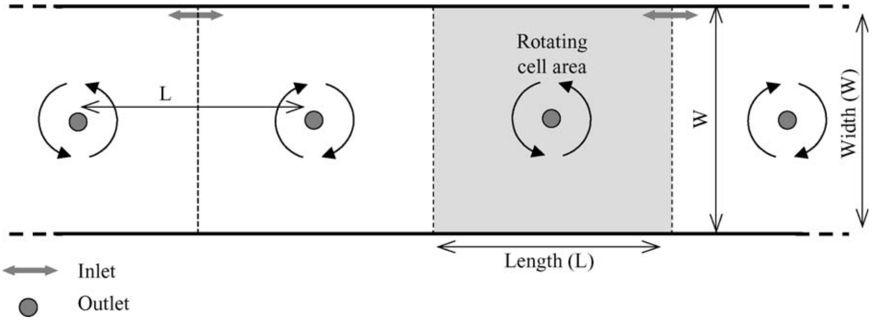

Fig. 1. Diagram of rectangular tank showing inlet and outlet placements, and rotating cell areas.

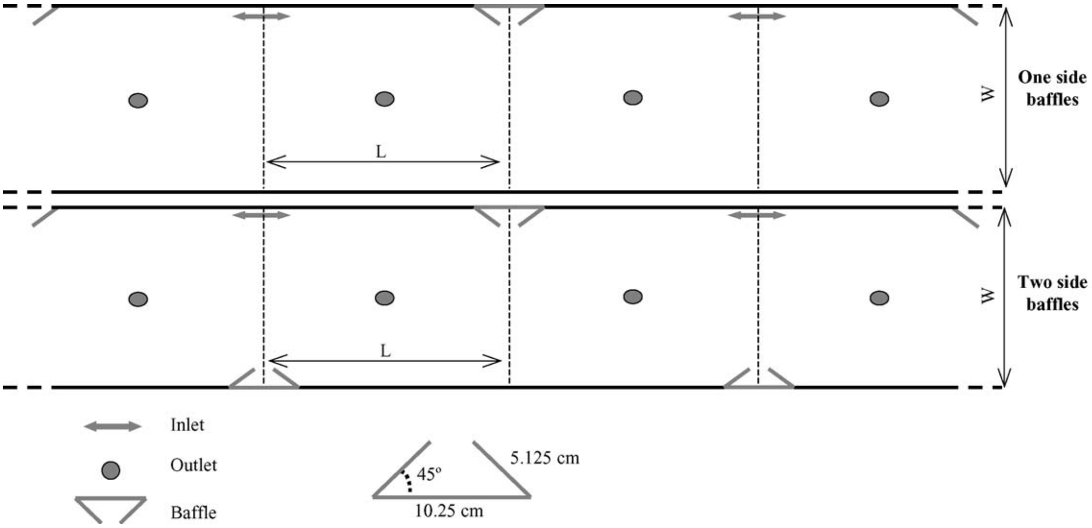

Fig. 2. Emplacement of baffles and entries in configurations with one and two side baffles.

The circular tank with a diameter of 49 cm had a single water entry and the drain was placed in the center of the tank bottom. The flow was then compared with those obtained in the rotating flow cells of rectangular tank configurations. Table 1 shows the geometric characteristics and flow rates of each configuration.

2.2. Flow visualization and image analysis

Particle Tracking Velocimetry technique (PTV) was used to obtain velocity fields in a horizontal plane at the midpoint of the water depth. Preliminary experiments conducted at different depths did not reveal significant differences between velocity fields.

Table 1
Geometric and hydraulic characteristics used in each configuration

	Length/width ratio of mixing cell area (*L*/*W*)	Baffles	Water inlet velocity (m/s)	Exchange rate (h^{-1})
Rectangular tank	0.95	None	0.301	5.94
		One side	0.589	5.94
		Two sides	0.589	5.94
	1.43	None	0.440	5.47
		One side	0.440	5.47
		Two sides	0.392	4.90
	1.91	None	0.637	5.94
		One side	0.637	5.94
Circular tank	1	None	0.473	5.47

PTV is a non-intrusive experimental method for investigating fluid flows, which allows the flow to be visualized by suspending neutrally buoyant tracer particles in the water volume. In this case, small particles of pliolita (Eliokem, pliolite S5E) with a density of approximately 1.05 g cm^{-3} and a diameter of around 0.5 mm were used. Sodium chloride was added to the tank to ensure the neutral buoyancy of the particles. A horizontal cross-section of the flow was illuminated at the midpoint of the water depth and the movement of the particles occupying the illuminated section was registered by a video camera placed 1.5 m above the water surface and digitized with a frame grabber card. Particle localization and tracking was achieved using specific software (Digimage) to determine the displacement, velocity and trace of each particle from sequences of frames. The data was summarized using an analysis package (Trk2Dvel) according to Dalziel (1999), which provided velocity maps of the mid-depth horizontal cross-section and longitudinal and lateral velocity profiles for each configuration. The average velocities for the horizontal section of a rotating flow cell were calculated for each experiment. Only intermediate cells were selected, in order to minimize the effect of an extra solid boundary in the end cells. A more detailed description of the application of PTV technique to flow characterization in fish production tanks can be found in Oca et al. (2004)

2.3. Hydrodynamic analysis of rotating flow cells

In a rectangular tank with several identical rotating flow cells, the impulse force from the inlet pipes to the cells F_i can be calculated using Eq. (1).

The impulse force F_i applied to the fluid in the tank that is moving at a velocity V_1, provides a power input P_i, which can be calculated as:

$$P_\mathrm{i} = F_\mathrm{i} V_1 = \rho Q (V_2 - V_1) V_1 \tag{2}$$

In a turbulent regime, the total resistive force to water circulation in the tank F_t can be calculated as:

$$F_\mathrm{t} = C_\mathrm{t} A \rho \frac{V_1^2}{2} \tag{3}$$

where C_t is the resistance coefficient of the tank and A is the wet area.

And the power consumption (P_t) due to the resistive force (F_t) is:

$$P_\mathrm{t} = F_\mathrm{t} V_1 = C_\mathrm{t} A \rho \frac{V_1^3}{2} \tag{4}$$

Assuming steady-state conditions, P_i is equal to P_t. Under such conditions, the following expression gives the experimental determination of the resistance coefficient for a specific tank:

$$C_\mathrm{t} = \frac{2Q(V_2 - V_1)}{A V_1^2} \tag{5}$$

C_t will be useful for evaluating the resistance of water circulation as a function of tank geometry and inlet and outlet placements.

In order to compare the velocity maps and profiles of experiments conducted with different impulse forces, velocity vectors can be shown non-dimensionally (V'), using the following expression:

$$V' = V \left(\frac{2Q(V_2 - V_1)}{A} \right)^{-1/2} \tag{6}$$

3. Results and discussion

3.1. Velocity distribution

Fig. 3 shows the flow patterns obtained in an intermediate single rotating cell area for each configuration analyzed; the vectors corresponding to water entries are not plotted because they are beyond the velocity range that can be detected by the equipment used. The velocity profiles on the longitudinal and lateral axes are shown in Figs. 4 and 5, respectively.

3.1.1. Effect of length/width ratio

Experiments with a length/width ratio (*L*/*W*) of 0.95 show a single large vortex generated by each discharge entry which covers almost the entire cell area. If the *L*/*W* ratio is increased from 0.95 to 1.43, the main vortex continues to occupy most of the rotating cell area and no significant dead volumes are created in the tank. The velocity profile on the longitudinal axis showed higher velocities at the farthest point from the water inlet than at the point closest to the water inlet. Importantly, this increase in the *L*/*W* ratio will make it easier for tanks to be constructed and adapted to a rotating cell flow pattern and requires fewer inlets and outlets for the same tank length.

When the *L*/*W* ratio is increased to 1.91, significant differences are observed in the flow pattern. The main vortex no longer covers the entire rotating cell area and significant dead areas with secondary vortices appear. Also, the vortex core is distorted and the velocities around it are very low. The center of the main vortex does not correspond to the center drain, since the vortex is displaced towards the opposite side of the discharge

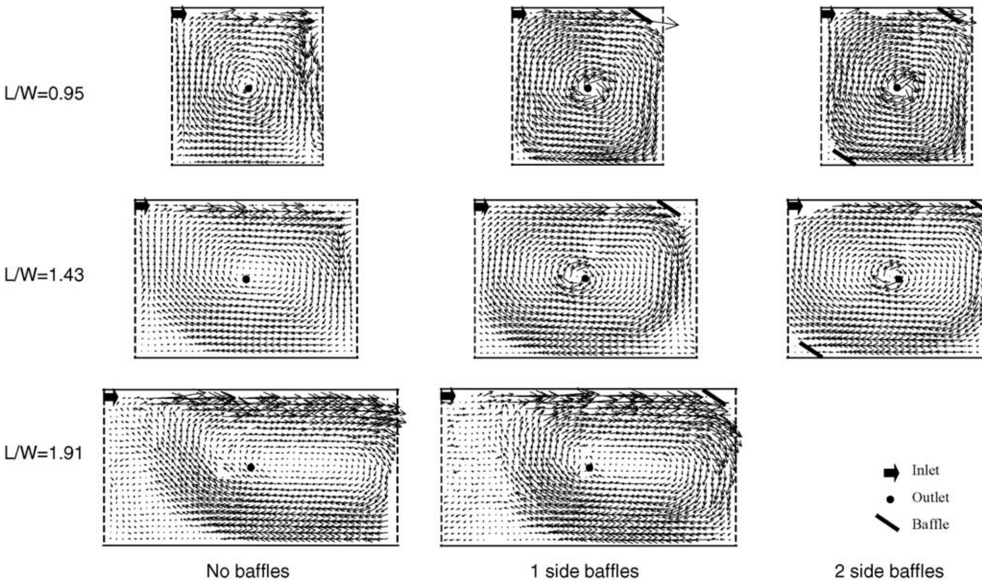

Fig. 3. Velocity field maps showing the flow patterns in a single rotating cell area, for configurations with *L*/*W* at 0.95, 1.43 and 1.91, and with 0, 1 and 2 side baffles.

jet. Average velocities in the center of the vortex are very low and the flow patterns are very unstable, thus vortex sizes vary with time. Similar results were obtained by Uijttewaal (1999), Weitbrecht and Jirka (2001) when analyzing velocity patterns in the dead zones of shallow water flows. The aspect ratios determined the number of eddies, with a single eddy created when aspect ratios were close to one and a secondary eddy created when aspect ratios were close to 2. These characteristics clearly demonstrate that the highest length/width ratio ($L/W = 1.91$) is unsuitable for the design of rotating cell tanks.

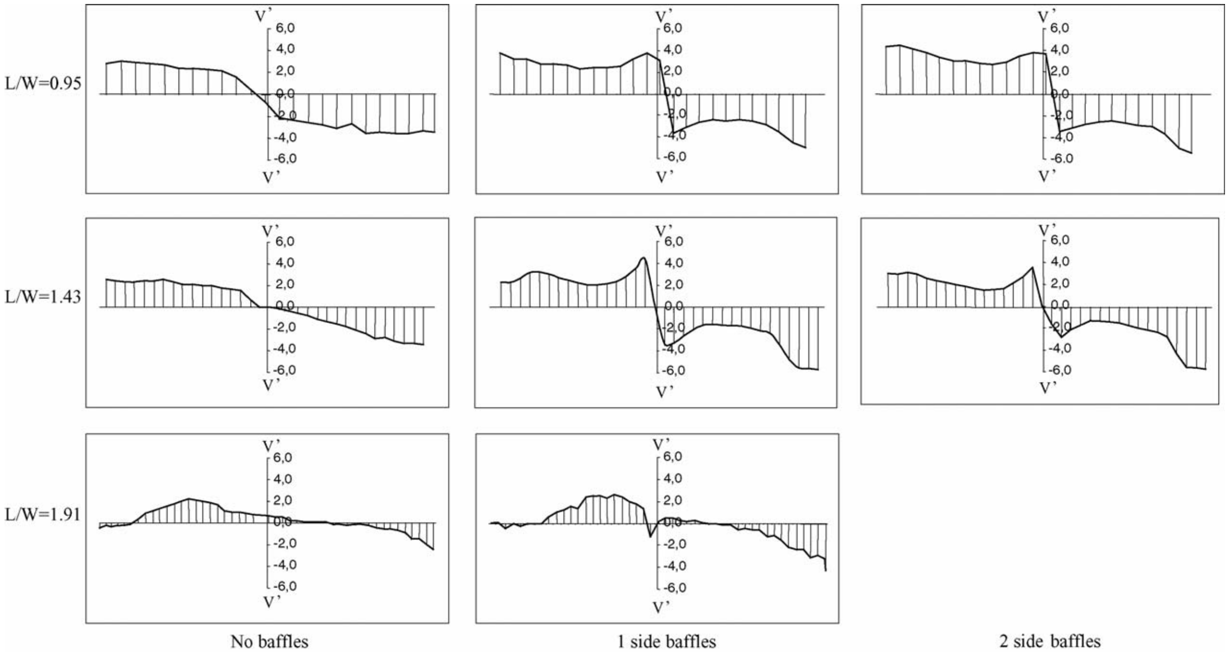

Fig. 4. Non-dimensional velocity (V') profiles in the longitudinal axis of the rotating cell area for each configuration.

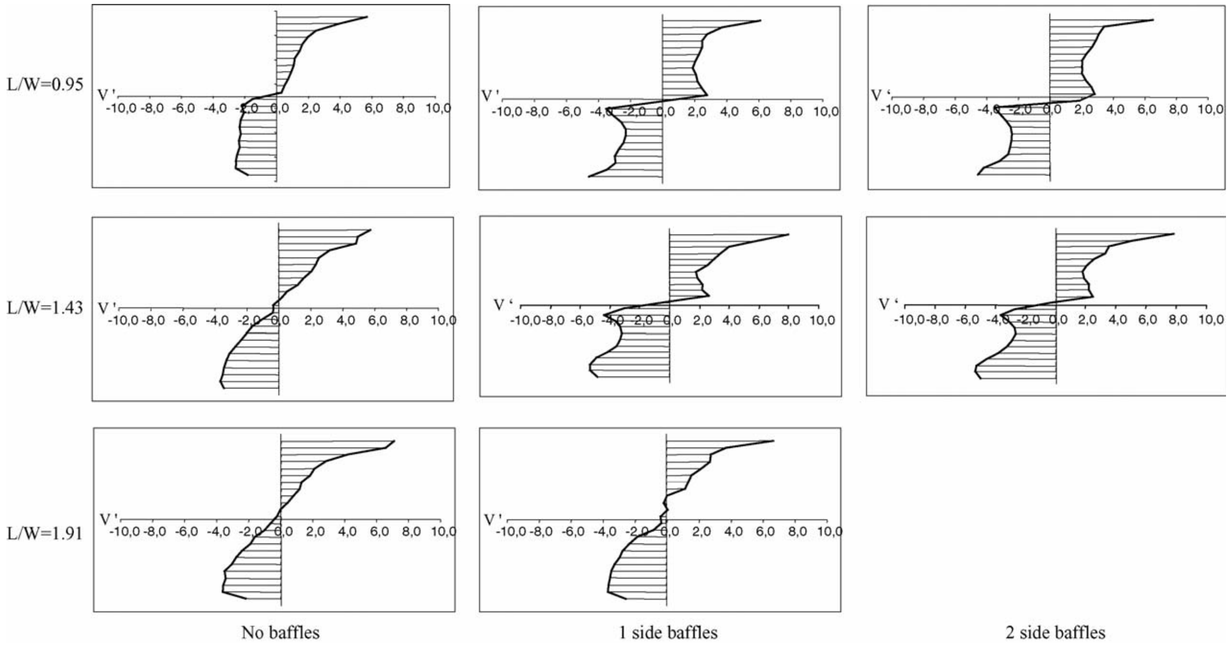

Fig. 5. Non-dimensional velocity (V') profiles in the crossing axis of the rotating cell area for each configuration.

3.1.2. *Effect of baffles*

The presence of baffles proved to be important in generating high velocities in the area around the center drain. These higher velocities are a key factor in the self-cleaning properties of the tank.

Velocity profiles along the longitudinal and lateral axes are shown in Figs. 4 and 5 for configurations with baffles and *L*/*W* ratios of 0.95 and 1.43. Note that the maximum velocities are registered in the outer perimeter of the vortex and these progressively drop to constant velocities in the central part of the vortex radius. The velocity increases again in the inner part of the vortex, due to effect of the free vortex formed by the water outlet. This increase can also be observed in velocity maps (Fig. 3). This type of flow pattern is very similar to that obtained in the equivalent experiment with a circular tank (Fig. 6) and is in good agreement with the circular tank flow described by Tvinnereim and Skybakmoen (1989) and Rasmussen and McLean (2004), with high relative velocities observed close to the central water outlet. In an experiment using a dual drain tank that discharged the majority of its flow through a drain located in its side wall and a smaller part through a center bottom drain, Davidson and Summerfelt (2004) found that water velocities near the tank center increased with higher drain-bottom flow rates.

No significant differences are observed between experiments using baffles in a single wall and others using baffles in both walls. Nevertheless, in experiments

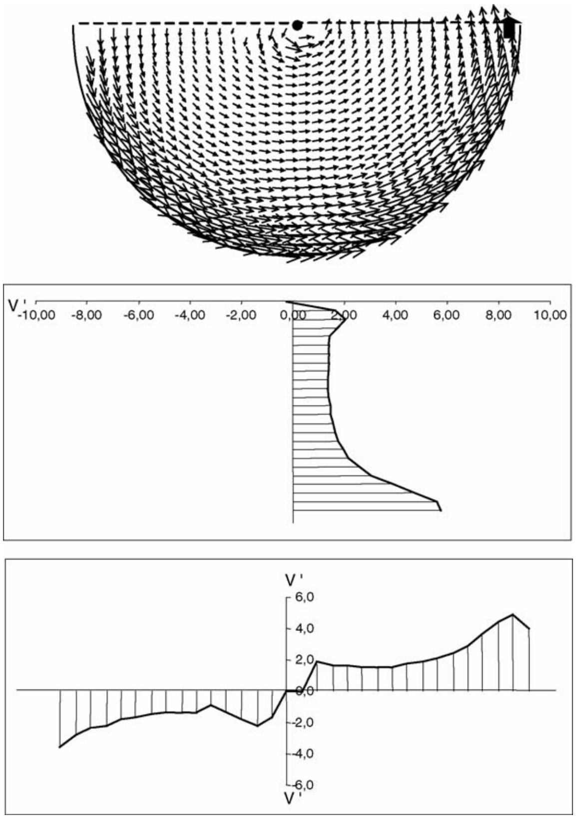

Fig. 6. Flow pattern and non-dimensional velocity (V') profiles in longitudinal and crossing axes in the circular tank.

where no baffles are used, velocities decrease from the perimeter of the rotating cell to the water outlet, and the effect of the free vortex on velocity profiles is small with a *L/W* of 0.95 and undetectable with higher *L/W* ratios.

With a *L/W* ratio of 1.91, the presence of baffles makes no appreciable contribution to improving water velocity distribution.

3.2. Resistance coefficient of the tank C_t

3.2.1. Influence of baffles and L/W ratio

The resistance coefficient of each configuration C_t (Eq. (1)) is shown in Table 2.

The values obtained are in excellent agreement with some of the qualitative observations described above. In rectangular tank configurations, lower C_t values are obtained with *L/W* ratios of 0.95 and 1.43 and with the inclusion of baffles. The presence of baffles in the same wall as the water inlets (one side baffles) decreases C_t values by approximately 30–35%. These results indicate that baffles placed in the midpoint of two opposite water inlets are important in driving the two water currents produced and in diminishing the friction losses caused by the collision of the two currents. The presence of a second group of baffles in the wall where no entries are placed (two side baffles) produces small variations in C_t values. The values obtained in experiments with *L/W* at 0.95 and 1.43 and with the inclusion of baffles are very close to those obtained in tests with a circular tank. When *L/W* is increased to 1.91, C_t values rise dramatically and are not visibly affected by the presence of baffles.

3.2.2. Expected results in larger scale tanks

The Reynolds numbers in these experiments, defined in terms of hydraulic diameter (approximately four times the water depth), were in the region of 6000, i.e., showing turbulent flow. Under these conditions, the flow pattern observed should be applicable to larger tanks (Tvinnereim, 1988; Tvinnereim and Skybakmoen, 1989; Chanson, 1999; Weitbrecht and Jirka, 2001). Nevertheless, C_t values can also be affected by the lower Reynolds numbers found in small-scale tanks, due to the greater importance of viscous effects (Chanson, 1999). The C_t values given here are useful for comparing different configurations, but full-scale research trials are necessary in order to determine definitive C_t values. These experiments would make it possible to compare not only the tank configuration, but also the influence of the water inlet arrangement, which has been shown to affect water velocities (Tvinnereim and Skybakmoen, 1989; Timmons et al., 1998).

Table 2
Resistance coefficient (C_t) obtained for each tank configuration

	L/W	C_t		
		No baffles	One side baffles	Two side baffles
Rectangular tank	0.95	0.14	0.09	0.08
	1.43	0.13	0.09	0.09
	1.91	0.18	0.17	–
Circular tank	–	0.08	–	–

Experiments conducted by Watten et al. (2000) in a rectangular tank 0.7 m deep with rotating cells 2.4 m long and wide, 1.3 exchanges per hour, an inlet velocity of 3.24 m/s, 4 water entries per rotating cell and without baffles, produced an average velocity of 0.12 m/s. The C_t value obtained from this data would be approximately 0.07—very similar to the values obtained in our small-scale experiments.

3.2.3. Control of velocities

By calculating a C_t value for the tank, it is easy to obtain the desired average velocities by adjusting the injected water flow rate (Q) and the water inlet velocity (V_2). From Eq. (5) we can write:

$$V_1 = \left(\frac{2Q(V_2 - V_1)}{AC_t}\right)^{1/2} \quad (7)$$

When the value of V_2 is much greater than that of V_1, this can be approximated as:

$$V_1 \approx \left(\frac{2QV_2}{AC_t}\right)^{1/2} \quad (8)$$

Q can be related to V_2 if the total area of inlet openings (A_0) are known:

$$Q = V_2A_0 \quad (9)$$

Eq. (8) can be re-written as follows:

$$V_1 \approx \left(\frac{2A_0}{AC_t}\right)^{1/2} V_2 \quad (10)$$

This shows that for a specific tank, a specific discharge device and a specific water depth, average water velocities will be roughly proportional to water inlet velocities. As an example, let us consider a tank 16 m long, 3 m wide and 1 m deep, with four rotating cells (area: 4 m × 3 m) and a discharge jet orifice with a diameter of 40 mm. If the required C_t were 0.08, the water discharge velocity needed to obtain an average velocity of 15 cm/s would be 378 cm/s, which corresponds to a flow rate of 19 L/s and 1.43 water exchanges per hour.

Relatively high, easily regulated average velocities with low energy consumption are usually obtained only with circular tanks. The tank configurations analyzed here would provide similar advantages in a rectangular tank.

The water velocity must be high enough to make the tank self-cleaning, but not greater than the desired fish swimming speed. The velocities required for self-cleaning have been estimated by various authors (Burrows and Chenoweth, 1970; Tvinnereim, 1988; Timmons and Youngs, 1991). The recommended velocities vary greatly according to faeces characteristics (Brinker et al., 2005) and range between 4 and 30 cm/s. These studies only considered the effect of water flow in the tank, disregarding the possible effect of turbulence generated by the fish, although this has been analyzed by other researchers (Burley and Klapsis, 1985, 1988; Watten et al., 2000; Rasmussen et al., 2005). Several authors have analyzed the optimal velocities for maintaining fish health, muscle tone and respiration, obtaining values of 0.5–2 times fish body length per second (Timmons and Youngs, 1991; Losordo and Westers, 1994).

4. Conclusions

Rotating flow cells in rectangular tanks can be generated using only a single inlet per cell. These cells may have very similar flow patterns to those obtained in circular tanks, if certain design criteria are followed in the placement of water inlets and outlets and the use of baffles to drive the water current.

The tank resistance coefficient (C_t) has been demonstrated as a useful tool for the evaluation of tank configurations in both rectangular tanks with rotating cells and in circular tanks. C_t values are very useful for adjusting the desired average velocity in the tank.

Increasing the distance of water inlets from L/W 0.95 to L/W 1.43 did not have a significant effect on the flow characteristics, the velocities achieved or the presence of dead volumes. A higher L/W value will make construction of rectangular tanks with rotating cells easier, since the number of water inlets and outlets required is reduced by 30%. A L/W ratio of 1.91 would dramatically reduce flow uniformity and create significant dead volumes.

Baffles attached obliquely to the same wall as the discharge jets, exactly in the midpoint between two opposite water inlets, contribute significantly to an increase in water velocities, particularly in the area closer to the center of the vortex where the water outlet must be placed. The flow pattern obtained under these conditions was very similar to those observed in circular tanks; the formation of a free vortex increasing the water velocity around the water outlet will allow the use of dual drains to separate suspended solids and to prevent sedimentation on the tank bottom.

In order to maintain the advantages of rectangular tanks relating to easier fish manipulation, it should be possible to turn baffles to the wall and to remove water inlets so as to leave the cross section free along the entire tank. An alternative water inlet and outlet should be constructed in order to allow water replacement during periods of fish manipulation.

Acknowledgement

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2.3. **Masaló, I.**, Reig, L., Oca, J. (2008) *Study of fish swimming activity using Acoustical Doppler Velocimetry (ADV) techniques.*

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Study of fish swimming activity using acoustical Doppler velocimetry (ADV) techniques

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Abstract

The suitability of using acoustic Doppler velocimetry (ADV) to study fish swimming activity is evaluated in this study. ADV makes it possible to detect and quantify the relationship between fish density and the turbulence generated by fish swimming activity and to show differences in fish swimming patterns during the scotophase (dark period) and photophase (light period), which has been previously described by other authors. Turbulence was evaluated using the root mean square of velocity (RMS) as an indicator of fish swimming activity, and an ADV probe with an internal sampling rate of 100 Hz, which took 25 velocity data per second.

Experiments at the laboratory scale using zebra fish showed a positive correlation between turbulence (RMS), caused by fish swimming activity, and density. The relationship between density and RMS was strongly linear ($r^2 = 0.964$). In an ongrowing farm, daily turbulence patterns caused by fish swimming activity were evaluated with sea bass at two densities: 35.5 kg m^{-3} (average weight of 48 g), and 11.8 kg m^{-3} (average weight of 11.7 g). Greater activity was detected during the photophase, indicating that light has a substantial affects sea bass swimming activity. Average RMS at a density of 35.5 kg m^{-3} was 3.632 and 2.428 cm s^{-1} during photophase and scotophase, respectively, while working at a density of 11.8 kg m^{-3}, average RMS was 1.728 and 1.419 cm s^{-1} during the photophase and scotophase, respectively.

ADV is a rapid and reliable method to evaluate fish swimming activity at laboratory scales as well as at commercial facilities. However, ADV configuration parameters must be properly chosen in order to obtain the highest possible number of good velocity data. Data post-processing was done by filtering velocity data using correlation (COR > 70), signal-to-noise ratio (SNR > 5) and *despiking* filters. COR provides a measure of quality of each velocity data, ranging from 0 to 100, and SNR indicates the intensity of the reflected acoustic signal expressed in dB. Finally, *despiking* filter eliminates spikes generated by fish located near the probe or between the probe and point of measurement. Post-processing showed that COR filter eliminated the higher number of velocity data.

Keywords: Fish swimming activity; Acoustic Doppler velocimetry; Turbulence

1. Introduction

Studying fish swimming activity is important, not only for understanding fish behaviour, but also for assessing the effects of fish swimming activity on water homogeneity and sediment dynamics in the tank (Rasmussen et al., 2005; Lunger et al., 2006). From a behavioural perspective, fish activity has traditionally been measured (1) visually (Wagner et al., 1995), (2) via automatically recorded interruptions of infrared light beams set across an aquarium (Iigo and Tabata, 1996; Sánchez-Vázquez et al., 1996), (3) by image processing (Kato et al., 1996) or (4) using acoustic telemetry (Bégout Anras et al., 1997; Bégout Anras and Lagardère, 1998, 2004;

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Schurmann et al., 1998; Bauer and Schlott, 2004). However, all these methods are either expensive, intrusive or time consuming, and are only useful when small numbers of fish are being studied.

The effects of fish activity on biosolids sedimentation caused by excretion and uneaten feed are well established. The shear stress due to turbulence generated by fish swimming activity helps prevent biosolids sedimentation and promotes resuspension of biosolids accumulated on the tank bottom. Therefore, the turbulence generated by fish is a valuable parameter for managing biosolids; this parameter will depend on the rearing conditions, such as fish size, density, etc. The relation between the turbulence generated by fish swimming activity and the turbulence needed to resuspend biosolids or prevent their sedimentation is indispensable to predict the existence of self-cleaning conditions in a fish tank.

Fish swim either by body and/or caudal fin (BCF) movements, or by using median and/or paired fin (MPF) propulsion. Pelagic fish swim by BCF movements, generating a jet of water in the opposite direction to which they are swimming. These jets include a regular pattern formed by vortices shed from fins and tail (Videler, 1993; Müller et al., 1997). In turbulent flow, unsteady vortices appear on many scales and interact with each other. The greater the fish activity, the greater the turbulence generated. Thus, knowledge of fish activity can be obtained by measuring turbulence inside a tank. Turbulence can be expressed as the root mean square (RMS) of the velocity (Wahl, 2006) (Eq. (1)):

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(v_i - v_{\mathrm{ave}})^2}{n}} \qquad (1)$$

where v_i represents the instantaneous velocity measurement; v_{ave} the mean velocity of the flow and n the number of instantaneous velocity measurements. RMS is expressed in velocity units.

In aquaculture tanks there are two sources of turbulence: free shear from the water inflow and friction drag and free shear from fish swimming activity. The hydrodynamics of tanks that do not contain fish have been widely studied (Klapsis and Burley, 1984; Burley and Klapsis, 1985; Cripps and Poxton, 1992, 1993; Oca et al., 2004; Oca and Masaló, 2007; Labatut et al., 2007). The effect of fish presence and the turbulence generated by their swimming activity on the flow pattern has also been studied, but only at the laboratory scale (Burley and Klapsis, 1985; Watten and Beck, 1987; Rasmussen et al., 2005; Lunger et al., 2006).

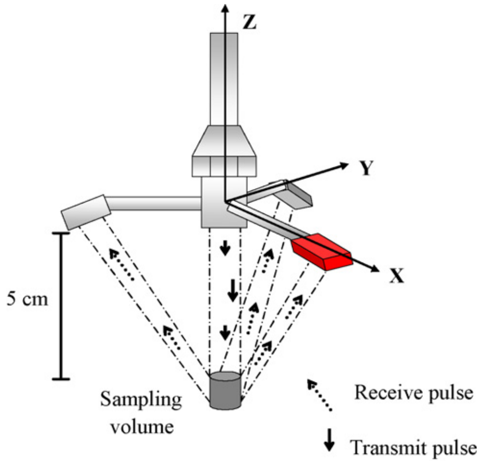

Fig. 1. Diagram of velocity sensor.

Acoustic Doppler velocimetry (ADV) has proven to be a rapid and reliable method for measuring turbulence (Lohrmann et al., 1994; Voulgaris and Trowbridge, 1998). An acoustic Doppler velocimeter is a sensor system based on the acoustic Doppler principle. It is suitable for high-resolution measurements of three-dimensional velocities at the laboratory and field scales. The ADV sensor consists of an acoustical signal transmitter and three receivers that are positioned in 120° increments around the transmitter (Fig. 1). The system operates by transmitting short acoustic pulses of known frequency along the vertical axis. The pulses are propagated through the water, and a fraction of the acoustic energy is scattered back in the sampling volume by small particles suspended in the water (e.g., suspended particles, sediments, small organisms, etc.). The echo from the sampling volume is picked up by the sensor receivers. The frequency shift between the transmitted pulse and the received echo is proportional to the water velocity. Depending on the measurement conditions, ADV configuration parameters (velocity range and sampling volume) must be properly chosen for turbulence measurements, and ADV data should not be used without suitable post-processing (Chanson et al., 2005).

ADV can be a very useful method for measuring turbulence produced by fish activity in laboratory- and commercial-scale tanks in a non-intrusive way, without restrictions concerning the number of fish. This method responds to increasing interest in studying fish swimming movements and behaviour under more natural and less confining conditions using new and innovative techniques and technologies.

The aim of this study is to determine the suitability of acoustic Doppler velocimetry (ADV) for studying fish swimming activity and for proposing the signal treatment and data analysis appropriate to evaluating turbulence in tanks containing fish. The relationship between density and the turbulence generated by fish will be tested, and the daily pattern of fish swimming activity in a production tank, with regular lighting periods, will be analysed using the proposed method.

2. Materials and methods

Experiments were carried out at the laboratory scale and in an ongrowing farm. A series of experiments at the laboratory scale with zebra fish (*Danio rerio*) were carried out to study the ability of ADV to detect the presence of fish from RMS measurements and to observe the differences in RMS obtained with different fish densities.

In a commercial aquaculture tank containing sea bass (*Dicentrarchus labrax* L.) in an ongrowing farm, two series of RMS measurements were taken to assess the turbulence generated by fish swimming activity over time. One series was taken with juveniles (48 g) during a short period of time (approximately 40 h) with high density (35.5 kg m^{-3}). The second series was taken with smaller fish (11.7 g) for a longer period (approximately 6 days), with low density (11.8 kg m^{-3}). Experiments were carried out under existing conditions at the facility (photoperiod, water temperature, feeding regime, etc.). The length of the experiments was dependent on farm restrictions.

2.1. Fish stocking conditions

2.1.1. Experiments at the laboratory scale

Experiments at the laboratory scale were carried out using a circular tank with a diameter of 49 cm and a water depth of 15 cm. Zebra fish (*D. rerio*) with a mean body weight of 0.58 ± 0.12 g, and standard length of 3.12 ± 0.23 cm were used. The tank was maintained at a 22.81 ± 1.53 °C and under natural photoperiod, with continuously filtered and aerated water (dissolved oxygen above 4.6 mg l^{-1}). Filter and aeration systems were placed outside the working volume to prevent them from affecting the measurements. The bottom of the glass tank was covered with sand to prevent reflecting echoes from the glass bottom being picked up by the receivers, which may occur when the probe is placed near the tank bottom (less than 5 cm from it) and the bottom is very reflective. A sand layer placed at the tank bottom decreases the percentage of data filtered. Fish were fed once a day at 6 p.m. by means of an automatic feeder.

The water flow was supplied by a vertical pipe placed near the tank wall, with five orifices (27 mm in diameter) driving water tangentially to the wall. A water outlet was placed in the centre of the tank bottom in order to achieve a circular flow pattern (Fig. 2). Different densities were tested (0, 1.10, 1.27, 2.5, 3.38, 7.17 and 7.61 kg m^{-3}) (Table 1).

At each density, five measurements (replicates) were taken. Each measurement was taken at a frequency of 25 Hz for 20 s, providing a total of 500 velocity data for each measurement (Table 2). This allows us to record frequencies between 0.05 and 12.5 Hz. Test measurements performed during 2 min, allowing us to record frequencies down to 0.0083 Hz, were also performed showing no additional frequency components.

The probe was mounted on a rigid structure which fixed it at the measurement point situated 12 cm from the tank wall, on the side opposite to the water inlet, and at a mid-water depth (7.5 cm from the tank bottom). The *X*-axis for velocity measurements was parallel to the tank wall tangent at the point closest to the wall (Fig. 2). Fish were transferred to the circular tank 48 h before the measurements were taken. All measurements were taken in the early morning, during photoperiod.

2.1.2. Experiments in an ongrowing farm

Experiments were carried out at *Méditerranée Pisciculture* (Salses le Château, France) in an octagonal 46 m^3 tank with a water depth of 167 cm and a circular flow pattern (Fig. 2). Water flow was supplied with a pipe with multiple orifices placed along the water depth, and a water outlet placed in the centre of the tank. The tank contained European sea bass (*D. labrax* L.).

Two set of experiments were carried out. The first experiment (Exp. 1) was carried out over a short period of time (approximately 40 h), with fish weighing a mean of 48 g, and with a stocking density of 35.5 kg m^{-3} (Table 1). The second experiment (Exp. 2) was carried out during a long period of time (approximately 6 days), with fish weighing a mean of 11.7 g, and with a stocking density of 11.8 kg m^{-3} (Table 1). Fish were exposed to an artificial photoperiod from 9 a.m. to 11 p.m. (lights on between 9 a.m. and 11 p.m.), and fed by means of a self-feeder. Water temperature was maintained at 15 and 22.5 °C in Exps. 1 and 2, respectively, and salinity maintained at 15‰ in both experiments.

Measurements were taken every 5 min throughout the experiment (Table 2). Each measurement took velocities with a frequency of 25 Hz for 20 s, and 500 velocity data were obtained. An adaptation period of 48 h, before the data were collected, was set in order to avoid alterations in fish behaviour due to the presence of

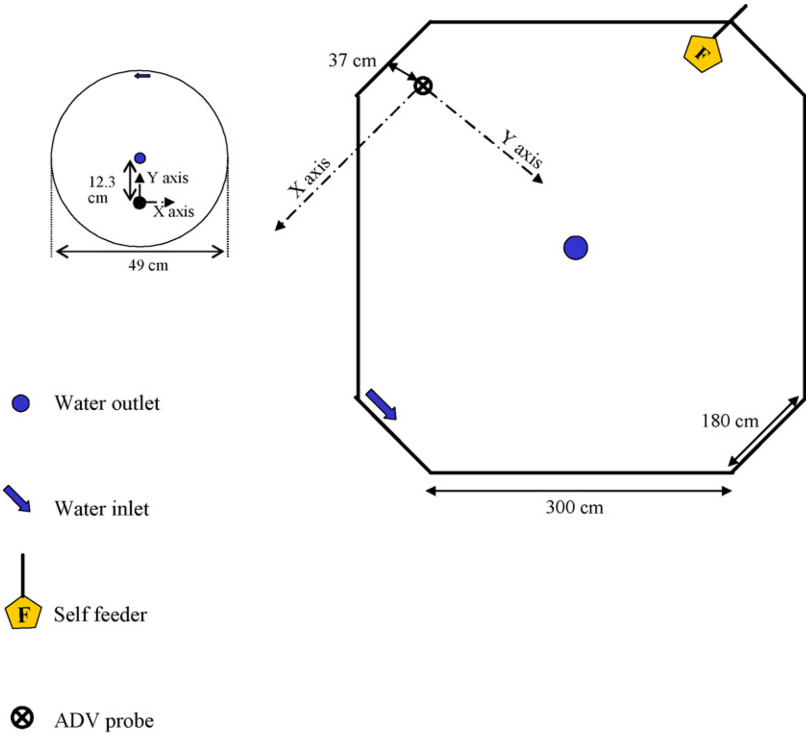

Fig. 2. Tank description and probe location in experiment with zebra fish (left), and in experiment with sea bass (right).

the probe. The probe was mounted on a rigid structure which fixed it at the measurement point situated at a depth of 85 cm. The *X*-axis for velocity measurements was horizontal and parallel to the tank wall closest to the probe (Fig. 2).

2.2. Data collection

The main swimming mode of adult sea bass is BCF (body and/or caudal fin movements). These pattern shows that the velocities in the *X*- and *Y*-direction (horizontal plane) are the most important (Videler, 1993; Müller et al., 2000, 2002; Nauen and Lauder, 2002), so, in the present study the RMS on the *X*-axis (RMS_X) is used as the indicator of turbulence generated by fish swimming activity.

Measurements were taken with an ADV sensor by Nortek (Nortek 10 MHz velocimeter); the sampling volume was placed 5 cm below the probe.

The sensor takes velocity data at an internal sampling rate of 100 Hz and transmits 100 acoustic pulses per second (100 pings). As the noise in a single ping is too high for practical use, the ADV averages a number of pings before outputting a velocity data. The number of pings averaged for each velocity data provides a specified sampling rate, which can range

Table 1
Fish stocking conditions in each experiment

	Zebra fish (laboratory)	Sea bass (ongrowing farm)	
		Exp. 1	Exp. 2
Tank volume (m^3)	0.03	46	46
Density (kg m^{-3})	0, 1.10, 1.27, 2.5, 3.38, 7.17, and 7.61	35.5	11.8
Average weight (g)	0.58	48	11.7
Temperature (°C)	22.8	15	22.5
Salinity (‰)	0	15	15
Photoperiod	Natural	P: 9 a.m. to 11 p.m., S: 11 p.m. to 9 a.m.	P: 9 a.m. to 11 p.m., S: 11 p.m. to 9 a.m.

P: photophase (light period) and S: scotophase (dark period).

Table 2
Velocity data acquisition in each experiment (laboratory with zebra fish, and in an ongrowing farm with sea bass)

	Zebra fish (laboratory)	Sea bass (ongrowing farm)	
		Exp. 1 bw: 48 g, *d*: 35.5 kg m^{-3}	Exp. 2 bw: 11.7 g, *d*: 11.8 kg m^{-3}
Frequency (Hz)	25 s^{-1}	25 s^{-1}	25 s^{-1}
Number of velocity data per measurement	500 (20 s) (5 replicates)	500 (20 s) (1 every 5 min)	500 (20 s) (1 every 5 min)
Total measurements	35	452 (40 h, approx.)	1666 (6 days, approx.)

bw: body weight and *d*: fish density.

from 0.1 to 25 Hz. A personal computer conditioned, processed and analysed the shift from the transmitted pulse and the received echo.

The sampling volume is defined by the cylinder formed by the sensor and the perpendicular axis. The diameter of the cylinder is a fixed value (7 mm). The user can choose a cylinder length of 3, 6 or 9 mm. Velocity measurements depend on the echo scattered in the sampling volume, and Nortek AS (2002) recommends choosing the highest sampling volume (9 mm in length).

In order to obtain a good velocity data, the user needs to take into account the correlation coefficient (COR) and the "signal-to-noise ratio" (SNR).

The ADV computes three correlation values (one for each acoustic receiver). The COR coefficient is a direct output of the Doppler velocity calculations, and provides a quality value for each velocity data, ranging from 0 to 100. Acceptable COR values are between 70 and 100 (Nortek AS, 2002).

The SNR indicates the intensity of the reflected acoustic signal expressed in dB. Intensity is determined by the concentration and size of the particles suspended in the water. The particles can be naturally occurring, suspended sediments, or artificial ("seeding"). Nortek AS (2002) recommends an SNR above 15 dB when the user is collecting raw data or above 5 dB when the user is collecting mean data. No artificial seeding was used in either experiment.

A critical aspect of ADV is the choice of an appropriate velocity range (VR) and sampling volume. As a general rule, the velocity range should always be set as low as possible, because data noise increases with increasing velocity range (the accuracy is 1% of velocity range at 25 Hz). Nevertheless, if the velocity range is set too low, aliasing of the velocity data may occur when velocities exceed the maximum range, causing occasional velocity "spikes" in data. Aliasing occurs when the measured phase difference between the two acoustic pulses transmitted and received by the ADV exceeds 180°. As the ADV cannot distinguish between a phase difference of 181° and −179°, the velocity recorded in the ADV file will change sign, producing a dramatic spike in the velocity data (Wahl, 2000). Aliasing may be generated when the effective distance to the boundary changes during sampling (Schlinder and Robert, 2004) or when there is interference from previous pulses reflected from boundaries with irregular profiles (Dey and Barbhuiya, 2005). In our experiments, aliasing occurred when fish were very close to the sampling volume.

2.3. Data post-processing

In the present study, turbulence analysis and post-processing of raw velocity data were carried out in three steps:

(1) SNR (>5) and COR (>70) were used to check the quality of the velocity data.
(2) A phase-space thresholding technique (*despiking* filter from Goring and Nikora, 2002) was used to remove spikes produced by aliasing. Nikora and Goring (1998) and Goring and Nikora (2002) developed techniques to eliminate spikes in steady flow situations. The method assumes that good ADV data are clumped within an ellipsoid (defined by a universal threshold ($\sqrt{}(\ln n\sigma)$, with n representing the number of data and σ the standard deviation) in phase-space plot of velocity, u, and approximations of the first (Δu) and second derivatives ($\Delta^2 u$). Spikes, which will be eliminated, are those points outside of elliptical projection on the ellipsoid onto the three principal phase-space planes (u–Δu, Δu–$\Delta^2 u$, u–$\Delta^2 u$).
(3) *Despiking* filter has been used in different fields, such as in the study of turbulence in flumes (Biron et al., 2004; Schlinder and Robert, 2004; Dey and Barbhuiya, 2005; Scott et al., 2005) and in the measurement of turbulence in estuaries (Chanson et al., 2005).

(4) Measurements with less than 50% of good data (more than 50% filtered) were removed.

COR, SNR and *despiking* filter (Steps 1 and 2 in post-processing) were applied using WinADV (Wahl, 2000), a post-processing freeware package designed specifically for the analysis of ADV files. Comparative analyses of COR and SNR filtered data and ‘‘despiked’’ data indicated that most of the spikes are removed by COR filtering (Chanson et al., 2005). Step 3 was applied at each measurement using a spreadsheet.

3. Results and discussion

3.1. Fish swimming activity

3.1.1. Experiments at the laboratory scale

The results show that RMS_X increased with increased densities (from 0 to 7.61 kg m^{-3}). RMS_X without fish (0 kg m^{-3}) had the lowest value (0.213 cm s^{-1}), due exclusively to the inflow pattern. When fish were present, RMS_X increased to a maximum value of 0.541 cm s^{-1} at the highest tested density (7.61 kg m^{-3}). RMS_X and density showed a linear relationship with a high correlation ($r^2 = 0.964$) (Fig. 3).

The average velocity on the *X*-axis during the experiments was 0.904 cm s^{-1}.

3.1.2. Experiments in an ongrowing farm

Experiments 1 and 2 showed higher RMS_X values during photophase than during scotophase, as can be seen in Fig. 4. Average RMS_X values measured during photophase in Exps. 1 and 2 were 3.632 and 1.728 cm s^{-1}, respectively, while during scotophase, RMS_X values in Exps. 1 and 2 were 2.428 and 1.419 cm s^{-1}, respectively.

While it was not possible to measure RMS_X values without fish, RMS_X values during photophase were 1.50 and 1.22 times higher than during scotophase for Exp.1 and Exp. 2, respectively. It is important to remember that the total RMS_X measured is not only due to fish activity, but also to the water current in the tank. Therefore, the above-mentioned ratios would increase if the increase of RMS_X produced by fish was considered in isolation.

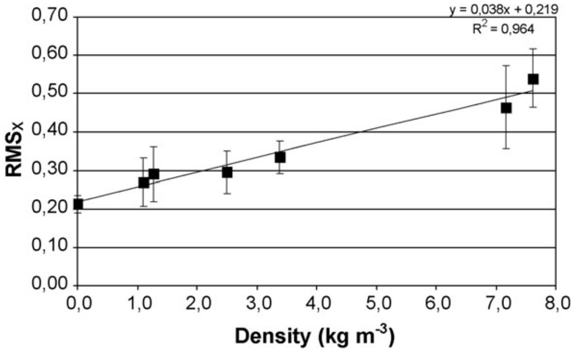

Fig. 3. RMS_X (cm s^{-1}) obtained at each density in experiments made with zebra fish.

Average velocities on the *X*-axis were 12.87 and 13.46 cm s^{-1}, respectively, for Exps. 1 and 2.

As expected, a comparison of the two experiments showed greater RMS_X in Exp. 1 than in Exp. 2, as both fish size and density were greater in Exp. 2 (48 g, 35.5 kg m^{-3}) than in Exp. 1 (11.7 g, 11.8 kg m^{-3}), and average velocities were similar.

An abrupt decrease in RMS_X values was observed every evening when the lights were switched off at 11 p.m. (Fig. 4). When the lights were switched on, RMS_X increased, and the mean value was always higher than the RMS_X obtained during scotophase in both experiments (Table 3 and Fig. 4). Taking a close look at the RMS_X 1 h after the lights were switched off, the RMS_X was always lower than the average values obtained during the scotophase (Table 3 and Fig. 5).

Some values above 6 cm s^{-1} ($\text{RMS}_X > 6\ \text{cm s}^{-1}$) in Exp. 1, and above 3 cm s^{-1} in Exp. 2 ($\text{RMS}_X > 3\ \text{cm s}^{-1}$) (Fig. 4) appeared mainly during light periods (photophase). These values may reflect fish reaction to noise made close to the tank. Experiments were carried out in an ongrowing farm, where staff were working everyday close to the tank and were likely sources of noise. Barnabé (1980) indicated that vibratory disturbances are likely to attract one or more individuals to the source of the vibration, thus generating an increase in turbulence (RMS).

Results obtained in this study concur with findings by Bégout Anras et al. (1997) and Bégout Anras and Lagardère (1998) that show greater activity during photophase. They found sea bass activity to be rhythmic, with fish adopting a diurnal activity rhythm when in a group (60 fishes sizing form 230 to 580 g), while single fish were mainly nocturnal. Bégout Anras and Lagardère (1998) described sea bass as a ‘‘diurnal and crepuscular’’ animal.

Similar to Bégout Anras et al. (1997) and Bégout Anras and Lagardère (1998), who determined that light is the dominant factor in the activity of sea bass, our study found that light has a considerable effect on sea bass swimming activity. The impact of light on fish swimming was especially evident when the lights were switched off and a significant decrease in swimming activity was observed. Eriksson (1978) also suggested that light is the main environmental variable affecting rhythmic patterns in fish.

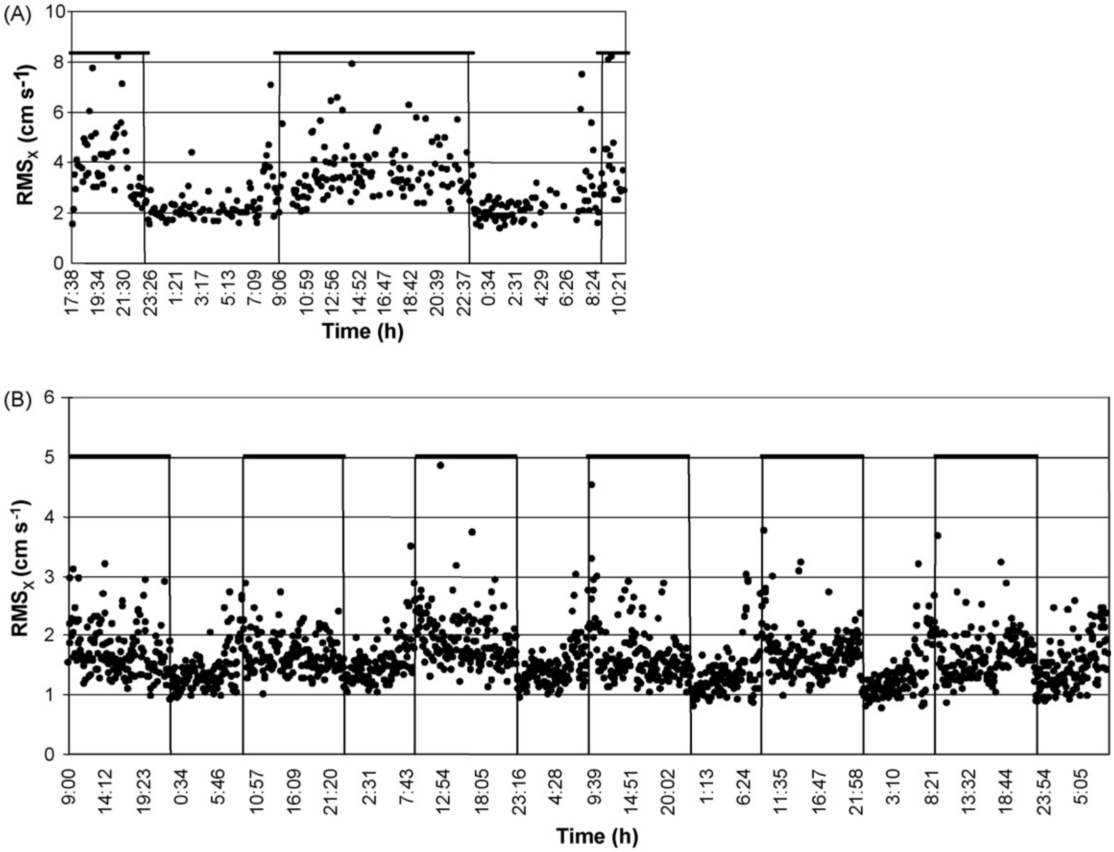

Fig. 4. (A) RMS$_X$ (cm s^{-1}) during Exp. 1 with sea bass at a density of 35.5 kg m^{-3} (average body weight: 48 g). (B) RMS$_X$ (cm s^{-1}) during Exp. 2 with sea bass at a density of 11.7 kg m^{-3} (average body weight of 11.8 g). Dark horizontal bars represent the light period (photophase).

3.2. Post-processing and data quality

Data post-processing is important for eliminating low quality velocity data values caused by proximity of fish to probe, or low signal reception. Here, the percentages of data removed in each experiment are presented, together with explanations.

3.2.1. Experiments at the laboratory scale

In experiments at the laboratory scale with zebra fish, measurements had a high mean of good velocity data per measurement (80.42 ± 15.44%), an average correlation of 96.27 ± 15.10, and an SNR of 18.58 ± 4.27 dB (Table 4). Velocity data elimination was due mainly to COR filtering. None of the 35

Table 3
RMS$_X$ mean in Exp. 1 (sea bass body weight 48 g, density 35.5 kg m^{-3}) during photophase (P), scotophase (S), and 1 h after the lights had been switched off (1 h after off)

Period	RMS$_X$ (cm s^{-1}) Mean	RMS$_X$ (cm s^{-1}) 1 h after off
S1	2.426 ± 0.867	1.892 ± 0.228
P2	3.632 ± 1.051	
S2	2.430 ± 0.976	2.144 ± 0.302

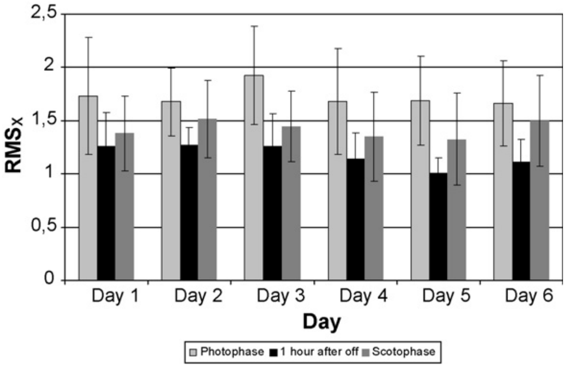

Fig. 5. Mean RMS$_X$ (cm s^{-1}) during photophase (light grey), scotophase (dark grey), and 1 h after the lights were switched off (black) in Exp. 2 with sea bass at a density of 11.7 kg m^{-3} (average body weight: 11.8 g).

Table 4
Results of data post-processing. bw: body weight, *d*: fish density

	Zebra fish (laboratory)	Sea bass (ongrowing farm)	
		Exp. 1 bw: 48 g, *d*: 35.5 kg m^{-3}	Exp. 2 bw: 11.7 g, *d*: 11.8 kg m^{-3}
Valid measurements	35 of 35 (100%)	355 of 452 (78.5%)	1650 of 1666 (99%)
Average good velocity data of valid measurements	80.42 ± 15.44%	66.02 ± 9.15%	81.86 ± 5.58%
Average COR of good velocity data of valid measurements	96.27 ± 15.10	91.89 ± 2.46	98.59 ± 1.06
Average SNR of good velocity data of valid measurements (dB)	18.58 ± 4.27	23.58 ± 6.90	44.57 ± 5.58

measurements taken at the laboratory scale were eliminated due to post-processing. The percentage of data filtered was always lower than 50%.

3.2.2. Experiments on an ongrowing farm

In experiments with sea bass raised on an ongrowing farm, the percentage of rejected velocity data was much higher. As a result of post-processing, 97 out of 452 measurements (21.5%) in Exps. 1 and only 16 out of 1666 measurements (<1%) in Exp. 2 were eliminated (Table 4). Non-rejected measurements had 66.02 ± 9.15% good velocity data per measurement in Exp. 1, and 81.86 ± 5.58% good velocity data per measurement in Exp. 2, and showed an average correlation of 91.89 ± 2.46 and 98.59 ± 1.06 in Exps. 1 and 2, respectively. SNR values for Exps. 1 and 2 were 23.58 ± 6.90 and 44.57 ± 5.58 dB, respectively.

Velocity data elimination was mainly due to COR filtering (Step 1 of post-processing). SNR filtering did not eliminate velocity data, as with these densities there were enough particles suspended in the water from fish excretion and uneaten feed.

A higher percentage of measurement elimination in Exp. 1 may have been due to the fact that in Exp. 1 the fish were bigger (48 g in Exp. 1 vs. 11.7 g in Exp. 2) and the density higher (35.5 kg m^{-3} in Exp. 1 vs. 11.8 kg m^{-3} in Exp. 2). With larger fish and higher densities there is greater probability of fish getting between the control volume and the receptors, thus producing disturbances in signal reception. For that reason, further experiments should set fish density limits that allow for effective use of ADV techniques to measure turbulence caused by fish swimming activity.

4. Conclusions

ADV makes it possible to detect and quantify increases in turbulence caused by fish at different densities and provides a quantitative measurement of swimming activity. Measurement of RMS using ADV techniques has proven to be a rapid and reliable method for quantifying turbulence in a tank containing fish, and shows that turbulence is closely linked to the level of fish swimming activity.

The application of the proposed method in an ongrowing farm allowed a daily cycle of activity among sea bass to be determined and to relate this cycle to photoperiod, obtaining results that are in good agreement with those described by other authors who have studied the behaviour of sea bass.

ADV measurements are very easy to take, require no tank handling or harm to fish, and make it possible to study fish swimming activity with a large number of fish (more than 45,000 in the present study in Exp. 2) in a non-intrusive way. It has been shown that the higher the density, the higher the velocity data eliminated by COR filtering.

Measuring turbulence caused by fish swimming activity can be useful for studying the effect of environmental conditions (photoperiod, temperature, dissolved oxygen, etc.) and rearing conditions (fish density, size, etc.) on fish activity, and for assessing the relationship between fish activity and processes of sedimentation and resuspension of biosolids. A comparative study of turbulence due to fish swimming activity and the turbulence needed to resuspend biosolids would be very useful for determining the rearing conditions necessary to prevent the sedimentation of biosolids and maintain self-cleaning conditions in fish tanks.

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2.4. **Masaló, I.**, Guadayol, O., Peters, F., Oca, J. (2008) *Analysis of sedimentation and resuspension processes of aquaculture biosolids using an oscillating grid.*

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Analysis of sedimentation and resuspension processes of aquaculture biosolids using an oscillating grid

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Abstract

Sedimentation and resuspension processes of aquaculture biosolids (non-ingested feed and faeces) are analysed using vertically oscillating grids as a source of turbulence in fluid tanks. An oscillating grid system consists of a container in which a grid is stirred vertically generating a well-known turbulent field that is function of amplitude and frequency of oscillation, distance between grid and measurement point, and mesh spacing of the grid. The grid used in this study had a mesh spacing of 1.2 cm, and was calibrated using different amplitudes (1, 1.5 and 2 cm), frequencies (from 1 to 6 Hz) and distances (2.4, 2.7 and 3 cm). After calibration, the turbulence needed to resuspend biosolids and to maintain them in the water column following different times of consolidation, and with biosolids of different origin, was analysed. It was observed that the turbulence needed to resuspend aquaculture biosolids increased with the time of consolidation. When the turbulence was decreased after a resuspension process, the next sedimentation of biosolids showed a hysteretic behaviour: turbulence needed to resuspend a fixed percent of biosolids from the tank bottom is substantially higher than that needed to maintain the same percentage suspended in the water column. Differences in resuspension behaviour of biosolids originated in different tanks were also observed.

The method provides useful information that can be compared with turbulence generated by fish swimming activity, in order to determine the culture conditions, which can promote self-cleaning conditions in a particular tank.

Keywords: Turbulence; Fish faeces; Solid waste; Resuspension; Oscillating grid

1. Introduction

Sedimentation and resuspension processes of aquaculture biosolids (fish faeces and non-ingested feed) are very important in aquaculture systems since they affect environmental conditions. Their accumulation in the tank bottom can lead to hypoxic conditions (Sumagaysay-Chavoso and San Diego-McGlone, 2003) that affect fish welfare and growth (Thetmeyer et al., 1999; Buentello et al., 2000). Nevertheless, if biosolids are maintained in the water column, or resuspended from the bottom, they may be removed from rearing areas with recirculation water, and can be separated by filtration or sedimentation processes (Cripps and Bergheim, 2000). Their maintenance in the water column will be determined by the turbulence level in the tank. Fish swimming activity and tank design (geometry and water inlet conditions, Oca et al., 2004) are the primary factors determining turbulence levels in the tank.

The study of resuspension and sedimentation processes of biosolids is especially complex, due to the cohesive properties of these materials. Biosolids are,

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mainly, aggregates of particles and/or microflocs subjected to aggregation and disaggregation processes, which modify their physical characteristics over time.

The density of aquaculture biosolids is very low, presenting a specific gravity (ratio of the density of a substance to that of a standard substance, water in this case) in the range of 1.005–1.250 (Chen et al., 1993; Patterson et al., 2003; True et al., 2004; Johnson and Chen, 2005; Droppo et al., 2007).

Turbulence generated by fish swimming activity has a great importance in aquaculture tank hydrodynamics, especially in intensive farming systems, where high fish densities are common. The higher the fish density, the higher the turbulence generated, and this turbulence can be enough to maintain biosolids in suspension or promote their resuspension from the tank bottom, even with low current velocity or a zero mean velocity. Chen et al. (1993), working in a recirculating system with brook trout (*Salvelinus fontinalis*) weighing 50 g and rainbow trout (*Oncorhynchus mykiss*) weighing 100 and 500 g, determined that more than 95% of the suspended particles in an aquaculture tank have a diameter less than 20 μm.

If biosolids are left undisturbed, they increase the resistance to resuspension as a result of consolidation of the bed (Mehta et al., 1989; Zreik et al., 1998; Orlins and Gulliver, 2003), or by sediment layer biostabilization (Droppo et al., 2007). The cause of biosolids consolidation at the bottom is the gradual compression and collapse of the particles and/or aggregates, when water that is in the pores is driven out. Mucus presence in aquaculture biosolids also increases this resistance to resuspension (Nowell et al., 1981).

In natural or artificial water streams, the transport of cohesive sediments is determined by the critical bed shear stress for erosion (perpendicular force needed to resuspend sediments) and for deposition (perpendicular force above which sediments are maintained in suspension) (Van Rijn, 1993). Flumes or tanks where the introduced bed shear stress is known are used to measure this erosion rate (Nowell et al., 1981; Portela and Reis, 2004; Droppo et al., 2007) or deposition rate (Neumeier et al., 2007).

Under low or zero mean vertical velocity, oscillating grids are a useful alternative tool for evaluating the dynamics of sedimentation and resuspension, and may be particularly useful in aquaculture tanks to study the effects of fish-generated turbulence.

Oscillating grids have already been used in the study of various environmental processes such as the initiation of sediment motion (Sánchez and Redondo, 1998; Medina et al., 2001), mixing in coastal waters (Carrillo et al., 2001), and turbulent mixing across density interfaces (Hopfinger and Toly, 1976; McDougall, 1979). Other authors (Tsai and Lick, 1986; Orlins and Gulliver, 2003) have used oscillating grids to study the resistance to resuspension of cohesive sediments originated in lakes with a high percentage of clay and silt. The method gives a quick and easy assessment of the turbulence levels characteristic of biosolids sedimentation and resuspension dynamics.

The purpose of this study is to evaluate the turbulence, generated by means of vertically oscillating grids, needed to resuspend aquaculture biosolids and to evaluate the minimum turbulence that allows biosolids to remain suspended in the water column. The effect of consolidation time and biosolids origin in the above mentioned processes would be analysed.

2. Material and methods

An oscillating grid consists of a grid, with a mesh size M (cm) (distance between the centers of two neighbouring openings), that oscillates around a mean position with an amplitude S (stroke in cm) at a known frequency f (Hz) (Fig. 1). In the fluid closer to the grid, there are large gradients in the turbulence level in the direction of grid oscillation. Beyond a distance 2 mesh sizes (M) from the grid, the movement of the oscillating grid generates isotropic turbulence with a zero mean flow in the container (Thompson and Turner, 1975; Hopfinger and Toly, 1976; Atkinson et al., 1987).

Turbulence can be expressed as the root mean square of the velocity (RMS). RMS is a statistical measure of the velocity fluctuation (Eq. (1)).

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n} (v_i - v_{\mathrm{ave}})^2}{n}} \qquad (1)$$

where v_i is the instantaneous velocity measurement, v_{ave} is the mean velocity of the flow, and n is the number of instantaneous velocity measurements. RMS is expressed in terms of velocity units.

Thompson and Turner (1975) found a linear relation between RMS and the grid oscillation frequency (f), and Hopfinger and Toly (1976) described an empirical equation that relates the RMS with oscillation frequency (f), stroke length (S), mesh spacing of the grid (M) and distance between the mid-point of the grid and the measurement point (z) (Eq. (2)).

$$\mathrm{RMS} = C \times M^{0.5} \times S^{1.5} \times f \times z^{-1} \qquad (2)$$

C is a constant that must be experimentally obtained because depends on the grid characteristics, which are

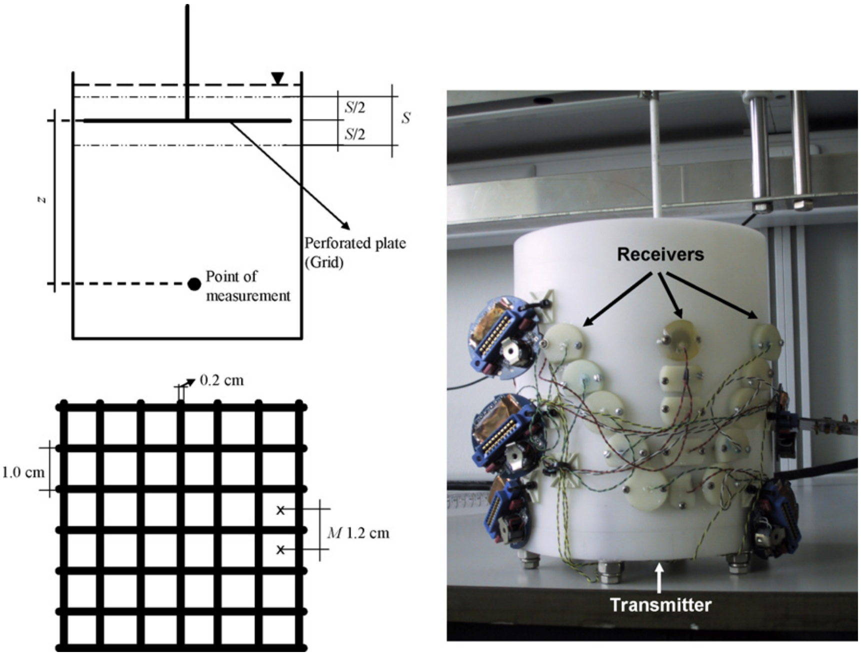

Fig. 1. Experimental setup (above, S is the stroke or amplitude of oscillations, and z the distance between the point of measurement and the grid), and characteristics of the perforated plate used in the present work (bottom, M is the mesh size). Right: acoustic transducers mounted in the custom made cylindrical container.

mesh spacing M and solidity (perpendicular area to the flow direction that is blocked by the grid bars). Hopfinger and Toly (1976) found a value of 0.25 for all three velocity components in a square tank (M of 5 and 10 cm, and solidity <40%), and De Silva and Fernando (1992) found values of 0.22 and 0.26 for the X–Y and Z axis, respectively (M of 4.76 cm and solidity of 36%). Solidity has to be less than 40%, allowing to obtain nearly isotropic turbulence with zero mean flow at distances greater than 2 M, and to avoid secondary circulations (Hopfinger and Toly, 1976; De Silva and Fernando, 1992).

We performed experiments to evaluate the feasibility of using oscillating grids for studies of resuspension and sedimentation processes with aquaculture biosolids. These experiments included, (a) the definition of the experimental device in order to be able to change the parameters S, f and z, (b) the calibration of the grid to find the relationships between S, f, z, and the RMS values, and (c) the experimental procedure to measure the suspended fraction of biosolids in the water column and the fraction settled in the tank bottom.

2.1. Experimental grid device

The experimental device consisted in a horizontal grid that moved vertically inside a container with a slightly larger horizontal section than the grid. A variable velocity gear head motor (K50 640, Kelvin, Madrid, Spain) connected to an eccentric arm, powered the vertically oscillating grid in a stainless steel structure. The motor had a nominal rotational velocity of 374 rpm and could be reduced to 1/20.

The grid was a perforated plate (stainless steel of 0.15 cm thickness) with 1 cm × 1 cm square orifices with a center-to-center spacing of 1.2 cm (M) (Fig. 1), presenting 30.5% solidity.

2.2. Grid calibration

In order to calibrate the flow introduced by the oscillating grid, we did velocity measurements under different oscillation conditions. Several types of sensors have been used to measure velocity in oscillating grid systems: hot-film probes (e.g. Thompson and Turner, 1975; Hopfinger and Toly, 1976), Laser Doppler Velocimeters (LDV, e.g. McDougall, 1979; De Silva and Fernando, 1992), Digital Particle Image Velocimetry (DPIV, e.g. Cheng and Law, 2001), acoustic Doppler velocimeters (ADV, e.g. Brunk et al., 1996; McKenna and McGillis, 2004). In this study we have used an ADV system, which allows measuring 3-dimensional velocities with a high frequency.

A custom made cylindrical container (made of Delrin, inner Ø 12.9 cm) was used to mount acoustic transducers flush to the inner wall (Nortek AS, Sandvika, Norway) (Fig. 1). Arrays of one acoustic transmitter and 3 acoustic receivers were aligned to measure 3-dimensional particle velocities using the Doppler effect at specific points inside the container. The system had 5 sets of transducers with measurement points at 23, 43, 64, 83 and 103 mm of height, and 23, 43, 64, 46 and 25 mm distance to the nearest wall, respectively. Data were acquired at 25 Hz for 1 min. Water was seeded with hollow glass spheres with a density close to that of water and a size around 11 μm (Spherical Hollow Glass Spheres, Potters Industries Inc.) to increase the strength of the signal and reduce noise. Measurements were conducted using sea water at approximately 22 °C.

In order to ensure steady state conditions inside the container, the oscillation of the grid was maintained at a constant stroke (S) and frequency (f) for 20 min before each measurement (Cheng and Law, 2001).

Three strokes ($S = 1$, 1.5 and 2 cm), three distances from the grid to the point of measurement ($z = 2.4$, 2.7 and 3 cm), and frequencies (f) from 1 to 6 Hz were used during calibration. All the distances (z) were above two mesh spaces ($z \geq 2$ M) ensuring isotropic turbulent conditions were achieved. The maximum frequency used was 6 Hz following McDougall (1979), who recommended the oscillation frequency to be smaller than 7 Hz in order to maintain horizontal mean velocities close to zero.

2.3. Grid measurement procedure

The study of resuspension and sedimentation processes required (1) the collection of biosolids and their placement with minimal disturbance in a container, (2) the progressive variation of the turbulence, and finally (3) the measurement of the percent of biosolids present in the water column at each turbulence level.

Biosolids were collected in a flow-through system from three 0.7 m^3 cylindrical fish tanks (tanks 0, 1 and 2) containing Sea bass (*Dicentrarchus labrax*, L.), with constant water temperature and salinity 37‰. Tank 0 contained an undetermined number of fish with different sizes. Tank 1 contained 11 fish weighting 129.45 ± 15.24 g and with a length 19.69 ± 1.99 cm, and tank 2 contained 69 fish weighting 79.54 ± 20.12 g and with a length 15.79 ± 1.69 cm. In all tanks, fish were manually fed *ad libitum* with commercial extruded pellets (Mistral 21, 49–52% protein, 33–41% fat and 10–15% lipids, ProAqua, S.L.).

Biosolids collection was made with a 300 ml glass jar through an outlet pipe in the false floor at the bottom of the fish tank. The jar was completely filled with water and biosolids, and immediately closed. Once in the laboratory, the jar was opened and the experimental containers were filled with the water and biosolids collected. We were extremely gentle during the whole procedure to minimize biosolids disturbance. Approximately a 0.5 cm layer of biosolids was placed in the bottom of the container. Then the experimental containers were slowly topped with water from the same fish tank, up to 12 cm in height.

Experimental containers were made of 1 cm thick transparent methacrylate. They were 25 cm high and had an 11 cm × 11 cm internal horizontal square section to minimize secondary circulation (Peters and Redondo, 1997).

For the assessment of biosolids resuspension (resuspension events), biosolids were left for 1 h and then the turbulence level was gradually increased every twenty minutes until all the biosolids were in the water column (no biosolids in the container bottom). For the assessment of aquaculture biosolids sedimentation (sedimentation events), when all the biosolids were in the water column the turbulence level was gradually decreased every thirty minutes. The final level was with still-water (RMS of 0 cm s^{-1}) during 30 min.

At each turbulence level, during resuspension and sedimentation events, water samples were withdrawn for analysis to quantify the presence of biosolids in the water column. Water (5 ml) was withdrawn from a point placed 5 cm below the free surface.

In order to measure the percent of biosolids suspended in the water column, two kinds of measurements were made: (1) turbidity was determined for all the samples after its dilution 1/5 with distilled water, using a spectrophotometer (Hach, model DR/2000) measuring FTU units (Formazin Turbidity Unit), and (2) total organic carbon (TOC) was also determined simultaneously with turbidity in some resuspension and sedimentation events. These samples were pressure-filtered through precombusted glass fibre filters (Whatman GF/F 0.7 μm) and the solid residue was analysed for total organic carbon with a TOC-Analyser (Shimadzu, TOC-V_{CSN}), connected to a Solid Sample Module (Shimadzu, Model SSM-5000A).

The percent of suspended biosolids was calculated from FTU values as:

$$\frac{\mathrm{FTU}_i - \mathrm{FTU}_{\min}}{\mathrm{FTU}_{\max} - \mathrm{FTU}_{\min}} \times 100 \qquad (3)$$

where FTU_i is the turbidity measurement at a fixed RMS value, $\mathrm{FTU}_{\min}$ is the measurement when all the biosolids are in the bottom of the container (RMS of 0 cm s^{-1}), and FTU$_{\max}$ is the measurement when all the biosolids are in water column (maximum RMS).

Similarly, the percent of suspended biosolids was calculated from TOC values as:

$$\frac{\mathrm{TOC}_i - \mathrm{TOC}_{\min}}{\mathrm{TOC}_{\max} - \mathrm{TOC}_{\min}} \times 100 \qquad (4)$$

where TOC$_i$ is the organic carbon measurement at a fixed RMS value, TOC$_{\min}$ is the measurement when all the biosolids are in the bottom of the container (RMS of 0 cm s^{-1}), and TOC$_{\max}$ is the measurement when all the biosolids are in water column (maximum RMS).

Both values (percent of biosolids calculated from FTU or TOC) where practically identical in those samples belonging to the series analysed using both methods. The relationship between TOC and FTU was strongly linear, with r^2 from 0.852 to 0.955 and $p < 0.001$, showing the turbidity as a good indirect measurement of the biosolids suspended.

2.4. Experimental procedure

Four set of experiments were done (Table 1):

1. Evaluation of the resistance to resuspension as a function of consolidation time;
2. study of a sedimentation process after resuspension using a gradual decrease of turbulence;
3. study of two consecutive processes of resuspension and sedimentation using a gradual increase in turbulence, followed by a gradual decrease in turbulence;
4. differences in resuspension and sedimentation processes of aquaculture biosolids originated in different tanks.

2.4.1. Evaluation of the resistance to resuspension as a function of consolidation time

Biosolids were collected in tank 0, and immediately placed in two different containers. With the first container, after 1 h of biosolids placement, the turbulence was progressively increased every 20 min (resuspension 1, 1 h of consolidation: R1CT1) until all the biosolids were in the water column (no biosolids in container's bottom). The experiment was repeated with the second container, after 48 h of biosolids placement (resuspension 1, 48 h of consolidation: R1CT48). At each turbulence level the percent of suspended biosolids was determined.

2.4.2. Study of a sedimentation process after resuspension

Biosolids were collected in tank 1. After 48 h of biosolids placement in the container the resuspension event began (resuspension 1, 48 h of consolidation: R1CT48) and the turbulence was increased gradually with steps of 0.17–0.18 cm s^{-1}. Each turbulence level was maintained during 20 min.

After total resuspension of biosolids, the sedimentation event was started (S1CT48), decreasing turbulence gradually (steps of 0.17–0.18 cm s^{-1}) every 30 min. The final turbulence level was with still-water (RMS of 0 cm s^{-1}) during 30 min. At each turbulence level the percentage of suspended biosolids was determined.

2.4.3. Study of two consecutive processes of resuspension and sedimentation

After the previous experiments (R1CT48 and S1CT48) this was repeated with a consolidation time of 48 h after the biosolids first resuspension event (resuspension 2, 48 + 48 h of consolidation: R2CT48 + 48 and S1CT48 + 48). Also, at each turbulence level the percent of suspended biosolids was determined.

2.4.4. Resuspension and sedimentation processes of aquaculture biosolids originated in different tanks

Experiments R1CT48 and S1CT48 (see Section 2.4.2) with biosolids collected in tank 1, were repeated with biosolids collected in tank 2 (R1CT48 and S1CT48) in order to evaluate the effect of resuspension and sedimentation events on biosolids with different origin. Also, at each turbulence level the percent of suspended biosolids was determined.

3. Results and discussion

3.1. Grid calibration

The constant C from Eq. (2) (Hopfinger and Toly, 1976) for the X and Y-axes, and for the Z-axis was determined. These calibration constants, obtained by linear regression between RMS (experimental values) and $M^{0.5}\,S^{1.5} f\, z^{-1}$ (Fig. 2), were 0.253 (r^2 = 0.841) for X and Y-axes (C_{x-y}) and 0.377 (r^2 = 0.957) for Z-axes (C_z) (Fig. 2). Both constants are slightly higher than those obtained by Hopfinger and Toly (1976) (C = 0.25) and De Silva and Fernando (1992) (C_{x-y} = 0.22, C_z = 0.26). These authors used larger containers, and also bigger center-to-center mesh spacing (M = 5 and 10 cm; and M = 4.76 cm). Thus, some differences in C values were expected.

Table 1
Summary of experiments

Experiment	Tank	Event	Number of resuspension/ sedimentation event	Consolidation time (h)
Evaluation of the resistance to resuspension as a function of consolidation time				
R1CT1	Tank 0	Resuspension	1	1
R1CT48	Tank 0	Resuspension	1	48
Study of a sedimentation process after resuspension				
R1CT48	Tank 1	Resuspension	1	48
S1CT48	Tank 1	Sedimentation	1	48
Study of two consecutive processes of resuspension and sedimentation				
R1CT48	Tank 1	Resuspension	1	48
S1CT48	Tank 1	Sedimentation	1	48
R2CT48 + 48	Tank 1	Resuspension	2	48 + 48
S2CT48 + 48	Tank 1	Sedimentation	2	48 + 48
Differences in resuspension and sedimentation processes of aquaculture biosolids originated in different tanks				
R1CT48	Tank 1, 2	Resuspension	1	48
S1CT48	Tank 1, 2	Sedimentation	1	48

3.2. Experimental procedure

3.2.1. Evaluation of the resistance to resuspension as a function of consolidation time

The resistance to resuspension was lower immediately after their collection (R1CT1) than after 48 h of consolidation in the tank bottom (R1CT48) (Fig. 3). For example, to resuspend 50% of biosolids in the water column after their collection an RMS_{x-y} of 0.60 cm s^{-1} was needed, while an RMS_{x-y} of 0.90 cm s^{-1} was needed to resuspend the same proportion when biosolids were left consolidating for 48 h.

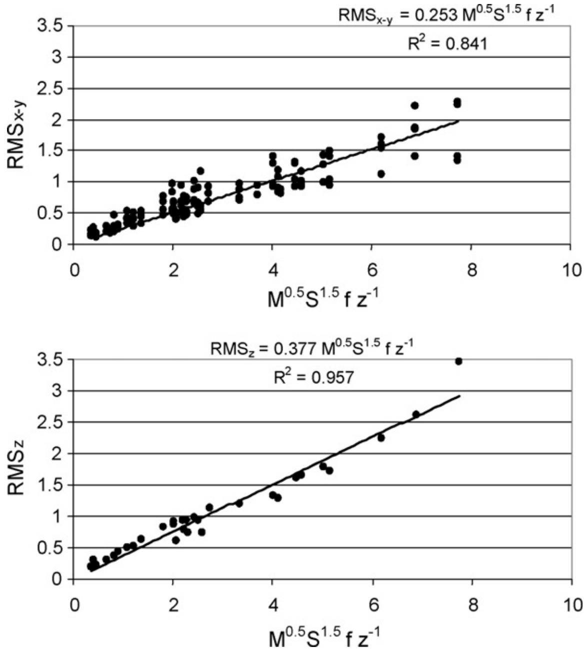

Fig. 2. Relationship between RMS experimental values (cm s^{-1}) and $M^{0.5}\,S^{1.5}\,f\,z^{-1}$ obtained in calibration experiments for X–Y (above) and Z (bottom) axis.

Our results demonstrate that resistance to resuspension increases with consolidation time. Similar results were found by Orlins and Gulliver (2003) for cohesive sediments in lakes. The increase in resistance to resuspension is a function of particle size, consolidation time and cohesiveness (Medina et al., 2001). Cohesiveness is enhanced by high fine particle content and a high organic matter ratio (Otsubo and Muraoka, 1988), and aquaculture biosolids present both characteristics.

Droppo et al. (2007) showed that consolidation time enhanced resistance in resuspension of biosolids accumulated under a rainbow trout (*O. mykiss*) cage, but they believed this increase was influenced strongly by biofilm integration on and within the surface sediment layer than by consolidation and dewatering effects. In our case the increase in the resistance to resuspension has been demonstrated. However, further experiments are necessary to study the presence of biofilm, and to separate the effects of consolidation and of biofilm integration.

Present results could be compared with turbulence generated in a tank with fish, in order to determine biosolids placement in the tank bottom. Masaló et al. (2008) determined the turbulence generated by fish swimming activity in a tank with a current velocity of 13 cm s^{-1} (approx.). With sea bass of 48 g and 35.5 kg m^{-3}, RMS_x in the tank was between 2.428 and 3.632 cm s^{-1}, and working with sea bass of 11.7 g and 11.8 kg m^{-3}, RMS_x was between 1.419 and 1.728 cm s^{-1}.

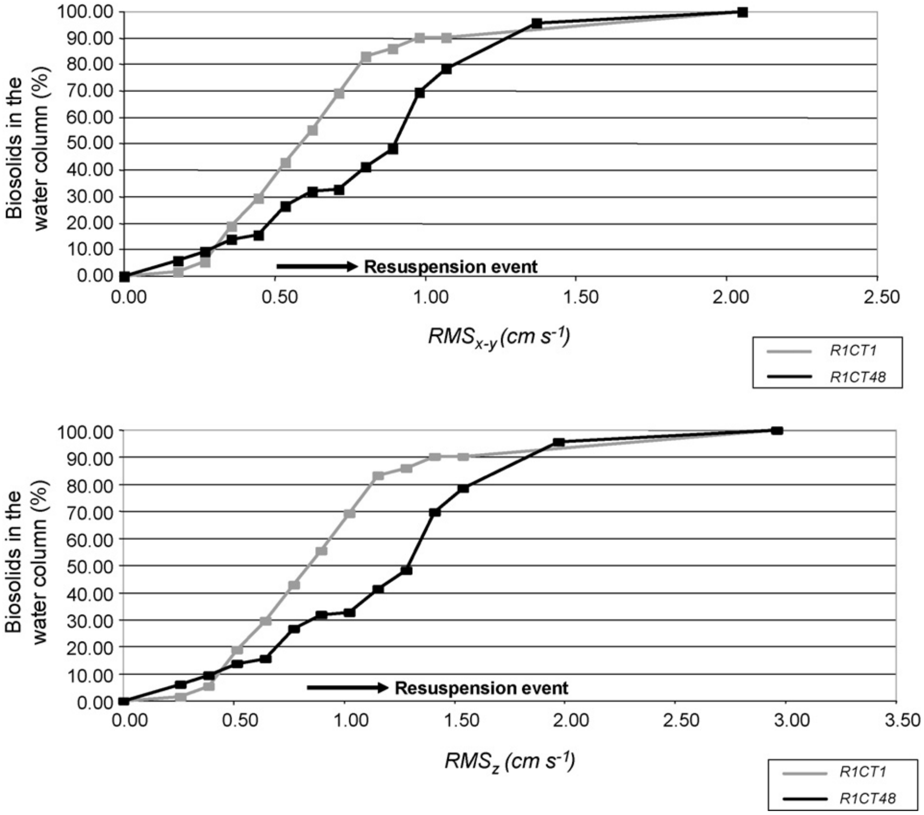

Fig. 3. Fraction of biosolids in the column as a function of the turbulence (RMS_{x-y} above, and RMS_z bottom) applied after collection (R1CT1, light grey line) and after 48 h of consolidation (R1CT48, black line).

3.2.2. *Study of a sedimentation process after resuspension*

After a total resuspension of biosolids when the turbulence was decreased gradually (sedimentation event), the percent of suspended biosolids, for the same turbulence level, was much higher than for the resuspension event (Fig. 4). For example, at an RMS_{x-y} of 0.35 cm s^{-1} more than 80% of the biosolids were still

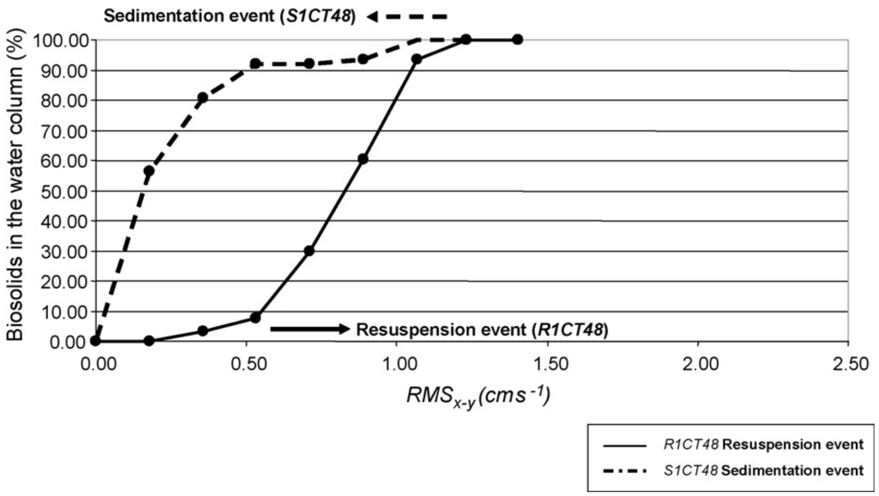

Fig. 4. Fraction of biosolids in the column during resuspension (filled line) and sedimentation (dashed line) as a function of the turbulence (RMS_{x-y}) applied after 48 h of consolidation (R1CT48 and S1CT48).

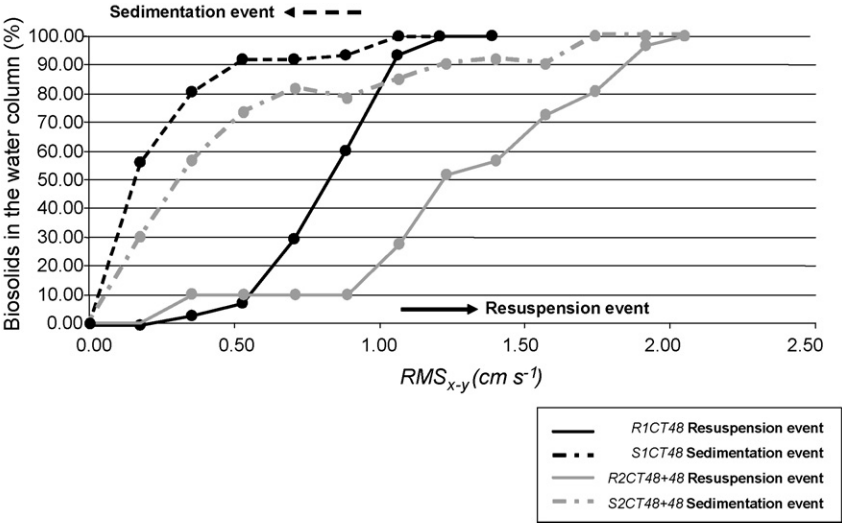

Fig. 5. Fraction of biosolids in the column during resuspension (filled line) and sedimentation (dashed line) event as a function of the turbulence (RMS_{x-y}) applied after 48 h of consolidation (R1CT48 and S1CT48, black line) and after 48 h of first resuspension event (R2CT48 + 48 and S2CT48 + 48, light grey line).

in the water column during the sedimentation event S1CT48, while during the resuspension event R1CT48, only about 3% of the biosolids were in the water column. This fact showed that the presence of biosolids in the water column greatly depends on the initial state, resulting in a hysteresis loop classified as counter clockwise. In this study the minimum RMS_{x-y} that allows maintaining 50% of the biosolids in the water column after their resuspension was around 0.20 cm s^{-1}, whereas the RMS_{x-y} needed to resuspend 50% of the biosolids placed in the bottom of the container was higher than 0.70 cm s^{-1}.

This hysteresis behaviour has also been found in cohesive sediments originated in estuaries (Portela and Reis, 2004), and in the sediment dynamics of snowmelt runoff streams (Langlois et al., 2005).

3.2.3. Study of two consecutive processes of resuspension and sedimentation

In experiments carried out following 48 h of consolidation time after the first resuspension (R2CT48 + 48, Fig. 5), the behaviour of the biosolids was similar to the R1CT48 experimental series. The curve showed again a hysteresis loop, with a higher fraction of biosolids in the water column for the same level of turbulence when their origin was the water column than when the origin was the bottom of the container.

During the second resuspension event the turbulence needed to resuspend the same amount of biosolids was higher than in the first resuspension event. For example, to resuspend 50% of the biosolids in the water column during the first resuspension event R1CT48 the RMS_{x-y} needed was lower than 0.90 cm s^{-1}, while in the second resuspension event R2CT48 + 48 it was higher (around 1.20 cm s^{-1}). A similar behaviour can be observed during the sedimentation event, were a higher turbulence was needed to maintain the same percent of sediments suspended during the second sediment event than during the first. For example to maintain 50% of the biosolids in the water column during sedimentation event the RMS_{x-y} needed were higher (around 0.36 cm s^{-1}) during the second sedimentation event, S2CT48 + 48, than during the first one, S1CT48, (around 0.20 cm s^{-1}). These differences suggest that during each consolidation biosolids particles aggregate, and as they become bigger and denser, their net sedimentation rates increase.

3.2.4. Resuspension and sedimentation processes of aquaculture biosolids originated in different tanks

As before in tank 1 (R1CT48), resuspension followed by a sedimentation event in tank 2 (R1CT48) also presented a hysteresis behaviour (Fig. 6). In experiments carried out after 48 h of consolidation time (R1CT48 and S1CT48), biosolids resuspension began in tank 1 when RMS_{x-y} was about 0.35 cm s^{-1}, and all the biosolids were in the water column at a RMS_{x-y} of 1.20 cm s^{-1}. In tank 2, biosolids resuspension began earlier, RMS_{x-y} about 0.20 cm s^{-1}, and all the biosolids were in the water column at a RMS_{x-y} of 0.90 cm s^{-1}, again, a lower turbulence than in tank 1.

The differences observed between biosolids collected in tanks 1 and 2 during the resuspension event

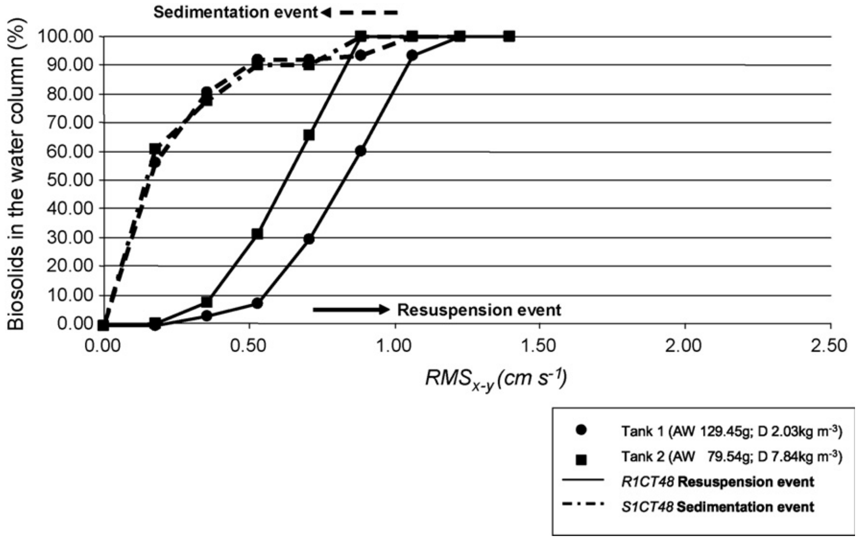

Fig. 6. Fraction of biosolids in the column during resuspension (filled line) and sedimentation (dashed line) events as a function of the turbulence (RMS_{x-y}) applied after 48 h of consolidation (R1CT48 and S1CT48 tanks 1 and 2). Tank 1 – circles – (D: 2.03 kg m^{-3}; AW: 129.45 ± 15.24 g), and tank 2 – squares – (D: 7.84 kg m^{-3}; AW: 79.54 ± 20.12 g): D: density, AW: average weight.

were not observed during the sedimentation event, where the behaviour of the curve was very similar in spite of the differences in the biosolids origin.

Differences observed in resuspension of biosolids originated in different tanks could be due to fish size. It has been observed that turbulence needed to resuspend biosolids originated in a tank with smaller fish (tank 2), is lower than turbulence needed to resuspend biosolids generated in tanks with bigger fish (tank 1). Magill et al. (2006) studied the settling velocity of faecal pellets working with Sea bream (*Sparus aurata*, L.) of 60, 240 and 380 g, and Sea bass (*D. labrax*, L.) of 50, 80 and 280 g, and pointed out that smaller fish produced smaller faecal particles. So, the smaller the particles, the lower the turbulence needed to resuspend them.

4. Conclusions

The oscillating grid method has proven adequate and logistically simple to determine the resistance of aquaculture biosolids to be resuspended by turbulence in the tank bottom, and to determine the minimum turbulence that allows biosolids to remain suspended in the water column. An increase in resistance to resuspension with consolidation time has been observed.

An hysteresis behaviour was observed in cycles of resuspension–sedimentation of biosolids. Their presence in the water column, at a fixed turbulence level, was higher during sedimentation events than during resuspension events. Thus, biosolids presence in the water column depends on the initial state.

When biosolids have been subjected to two consecutive consolidation and resuspension processes, the turbulence level needed to resuspend them in the second resuspension was higher, and the second sedimentation process occur under a higher turbulence level than the first one.

We have observed differences in resuspension behaviour of biosolids originated in tanks containing different fish sizes. Lower turbulence was needed to resuspend biosolids originated by smaller fish. Thus, the method allowed the detection of differences in the resuspension of biosolids of different origin.

Among the many applications of the method here described, we could point to the determination of the optimal self-cleaning conditions in fish tanks under specific culture conditions, knowing the turbulence generated by fish swimming activity that can be measured using ADV techniques according to the method described by Masaló et al. (2008). It can also be applied to investigate the effects of different binders added to feeds in the resistantance to resuspension of biosolids, and also to investigate the effect of different fish species and sizes on the resuspension, again as a means of optimizing fish tank culture conditions.

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3. SUMMARY OF RESULTS

3. SUMMARY OF RESULTS

The experiments were designed in four stages to study tank hydrodynamics, to quantify fish swimming activity, and to quantify the turbulence needed to resuspend biosolids in aquaculture tanks and/or the minimum turbulence under which biosolids remain resuspended. The specific work carried out in the four stages is reported in separate articles:

1) Analysis of flow patterns in rectangular rearing tanks to evaluate configurations with different water inlet characteristics and to determine which configuration provides the most homogeneous conditions.

   ARTICLE 1: Oca, J., **Masaló I.**, Reig, L. (2004) *Comparative analysis of flow patterns in aquaculture rectangular tanks with different water inlet characteristics.* Aquaculture Engineering 31 (3-4), pp 221-236

2) Exhaustive study of rotating-flow cells in rectangular tanks.

   ARTICLE 2: Oca, J., **Masaló, I.** (2007) *Design criteria for rotating flow cells in rectangular aquaculture tanks.* Aquacultural Engineering 36 (1), pp 36-44

3) Proposal of a method for measuring the turbulence generated by fish swimming activity in a rearing tank

   ARTICLE 3: **Masaló, I.**, Reig, L., Oca, J. (2008) *Study of fish swimming activity using Acoustical Doppler Velocimetry (ADV) techniques.* Aquacultural Engineering 38 (1), pp 43-51

4) Proposal of a method for determining the turbulence needed to resuspend biosolids and prevent sedimentation; comparison of this turbulence with those generated by fish swimming activity.

   ARTICLE 4: **Masaló, I.**, Guadayol, O., Peters, F., Oca, J. (2008) *Analysis of sedimentation and resuspension processes of aquaculture biosolids using an oscillating grid.* Aquacultural Engineering 38 (2), pp 135-144

3.1. ANALYSIS OF FLOW PATTERN IN RECTANGULAR REARING TANKS

The flow pattern in tanks with different water inlet characteristics was analysed by applying particle tracking velocimetry (PTV) techniques to scale models in the laboratory. PTV can determine the full velocity field in any cross section of flow inside the tank.

Four different water inlet and outlet configurations were tested in a tank measuring 1.30*0.40*0.20 m:

1) A single upright waterfall (fall height of 3 cm) with an outlet in the centre of the wall opposite the inlet. Three exchange rates (4.5, 6.5 and 9.1 h^{-1}).
2) A single horizontal submerged inlet with an outlet in the centre of the wall opposite the inlet. Exchange rate of 5.0 h^{-1}.
3) Multiple upright waterfalls (fall height of 2.5 cm) with an outlet in the centre of the wall opposite the inlet. Exchange rate of 9.1 h^{-1}.
4) Tangential inlets to produce rotating flow pattern with outlets placed in the eddy centre on the tank bottom. Exchange rate of 9.0 h^{-1}.

The results showed that a single submerged inlet generated a bypass current with large lateral eddies and dead zones (Figure 7, Article 1). The velocities were distributed heterogeneously. When a single waterfall inlet was tested with a fall height of 3 cm, an area of intense mixing with a radius of 2.5 times the water depth was observed around the inlet (Figure 3, Article 1); the area also contained a vertical eddy with a length of 2.5 times the water depth that was not affected by the flow rate (Figure 4, Article 1). Beyond this area, we observed large eddies and areas of recirculation with dead zones in the middle (Figure 5, Article 1). The flow pattern was highly unstable over time (Figure 6, Article 1).

Configurations with multiple waterfalls showed overlapping vertical eddies close to the inlet and perpendicular to the tank length. These eddies produced better mixing in the first section of the tank, which has a length of approximately four times the water depth (Figures 8, 9 and 10, Article 1). Beyond this area, the flow field became more homogeneous as the number of waterfalls increased (a high degree of homogeneity was attained when the distance between inlets was reduced from 3.8 to 2.5 times the water depth) (Figure 11, Article 1).

Finally, the configuration with tangential inlets and with outlets placed in the bottom centre of the cell area showed a circular flow pattern (Figure 12, Article 1) with a slightly elliptical shape, since the longest diameter was 1.25 times greater than the shortest one. The flow pattern was very stable over time and the water velocities along the entire length of the tank were greater and more homogeneous than in the previous configurations.

3.2. STUDY OF ROTATING-FLOW CELLS IN RECTANGULAR TANKS

We tested different configurations that create rotating-flow cells in a rectangular tank (200*35*0.06 cm). Three cell length/width ratios (*L/W*) were analysed: 0.95 (6 vortices), 1.43 (4 vortices) and 1.91 (3 vortices). We also studied the effect of placing baffles in one of the side walls or in both of the side walls of the tank between two water inlets, with an inclination of 45º. All of the configurations included a single water inlet per cell and a drain placed in the centre of the tank bottom between two consecutive water inlets. Experiments were also performed in a circular tank (49 cm diameter) so that the results could be compared. PTV was used to determine the flow patterns and velocity distributions in an intermediate single rotating cell.

A main single vortex occupying the whole cell area was observed in experiments without baffles and with *L/W* cell ratios of 0.95 and 1.43 (Figure 3, Article 2). However, when the *L/W* cell ratio was increased to 1.91, secondary eddies appeared and dead zones were observed in the longitudinal axes of the tank. In addition, the centre of the main vortex did not coincide with the location of the drain, which led to low velocities in the surrounding area.

The baffles also affected the flow pattern and velocity distribution when *L/W* cell ratios of 0.95 and 1.43 were used: the water velocities around the water outlets were higher than in the configurations without baffles (Figure 3, 4 and 5, Article 2). No significant differences were observed between the configuration with baffles in one side wall and the configuration with baffles in both side walls. The increase in velocity close to the outlet with *L/W* cell ratios of 0.95 and 1.43 and with baffles was also observed in the circular tank (Figure 6, Article 2). No velocity increase was observed close to the outlet with a *L/W* cell ratio of 1.91, and the presence of baffles did not improve the flow pattern (Figures 3, 4 and 5, Article 2).

We defined a tank resistance coefficient C_t to evaluate the resistance to the circulation of water produced by each tank configuration (Equation 5, Article 2).

$$C_t = \frac{2Q(V_2 - V_1)}{AV_1^2}$$

Equation 5, Article 2

where C_t is the tank resistance coefficient (dimensionless), Q is the flow rate, V_1 is the mean circulation velocity, V_2 is the water inlet velocity (jet velocity) and A is the wet area.

Higher C_t values were observed with *L/W* ratios of 0.95 and 1.43 without baffles (0.14 and 0.13) and with a *L/W* cell ratio of 1.91 with and without baffles (0.18 and 0.17) (Table 2, Article 2). Higher C_t values produce lower average velocities with equivalent impulse forces.

The C_t values were higher for configurations in which dead zones emerged. For example, the lowest C_t values were found in configurations with *L/W* cell ratios of 0.95 and 1.43 and with baffles in one side wall (C_t of 0.09 for both cases) or in both side walls of the tank (C_t of 0.08 and 0.09, for *L/W* cell ratios of 0.95 and 1.43, respectively). In these configurations, the value of C_t

was very close to that obtained in the circular tank (0.08). The highest C_t value was obtained with a L/W of 1.91 without baffles (0.18); however, this value was very close to the one obtained with the same L/W cell ratio but with baffles in one side of the tank wall (0.17).

Once the value of C_t has been determined, the desired velocity inside the tank (mean circulation velocity V_1) is obtained by adjusting the injected flow rate (Q) and the water inlet velocity (V_2) (Equation 10, Article 2).

$$V_1 \approx \left(\frac{2A_0}{AC_t}\right)^{1/2} V_2 \qquad \textbf{Equation 10, Article 2}$$

where A_0 is the total area of water inlet openings.

3.3. QUANTIFICATION OF FISH SWIMMING ACTIVITY

We assessed the suitability of acoustic Doppler velocimetry (ADV) for measuring the turbulence produced by fish swimming activity. A proposal was also made for signal treatment and data analysis.

Turbulence was evaluated at the laboratory scale and in an ongrowing farm by measuring the root mean square of velocities in the x-axis (RMS_x) at a point in the tank in the middle of the water depth. In the laboratory, zebra fish (*Danio rerio*) were used to determine whether ADV can detect the presence of fish and to relate fish density to turbulence. In the ongrowing farm, sea bass (*Dicentrarchus labrax*) were used to determine the turbulence generated over time by swimming activity in two tanks with different fish densities and sizes (Table 1, Article 3).

Three filters were applied in the data post-processing stage: Signal-to-Noise Ratio (SNR>5), correlation (COR>70) and a despiking filter. Measurements with less than 50% of good velocity data were rejected.

The laboratory results showed that turbulence (RMS_x) increased linearly with fish density to a high degree of correlation (r^2=0.964) (Figure 3, Article 3).

The farm results showed that the photoperiod had a strong effect on fish activity. The RMS_x values were on average 1.50 and 1.22 times higher during the photophase (light period) than the scotophase (dark period), respectively, in the two experiments. The average values of RMS_x during the photophase and scotophase were 3.632 and 2.428 cm s^{-1} for Experiment 1 (high density: 35.5 kg m^{-3} and 48 g average weight), and 1.728 and 1.419 cm s^{-1} for Experiment 2 (low density: 11.8 kg m^{-3} and 11.7 g average weight).

Interestingly, a sharp decrease in RMS_x values was observed when the lights were switched off (Figure 4 and 5, Article 3), which demonstrates that light has a strong effect on sea bass activity. RMS_x values increased in both experiments (high and low density) when the lights were switched on, and higher values were obtained during the photophase than the scotophase.

Velocity data elimination was mainly due to *COR* filtering in all experiments (both laboratory and ongrowing farm). No measurements were eliminated from the laboratory experiments due to post-processing, but 97 of 452 measurements (21.5%) and 16 of 1666 measurements (<1%) were eliminated from Experiments 1 and 2, respectively, in the ongrowing farm tests.

3.4. QUANTIFICATION OF THE RESUSPENSION AND SEDIMENTATION OF AQUACULTURE BIOSOLID WASTE

We used a vertically oscillating grid adapted to the specific characteristics of aquaculture biosolid waste to analyse the sedimentation and resuspension processes. The turbulence generated by oscillating grids was evaluated measuring the root mean square (*RMS*) of velocities. The *RMS* generated by the oscillating grid inside a container holding a fluid is a function of a constant C (which has to be experimentally determined), frequency (f), distance between measurement point and grid (z), length of oscillation (stroke S) and mesh spacing (M).

An oscillating grid with a mesh spacing of 1.2 cm was calibrated using frequencies from 1 to 6 Hz, distances between the measurement point and grid of 2.4, 2.7 and 3 cm, and oscillations of 1, 1.5 and 2 cm. Two constants were determined from calibration experiments (Figure 2, Article 4): one for the x- and y-axes (C_{x-y}=0.253, r^2=0.841) and one for the z-axis (C_z=0.377, r^2=0.957).

After calibration, four types of experiments were carried out (Table 1, Article 4):

1) Evaluation of the resistance to resuspension as a function of consolidation time (1 hour and 48 hours of consolidation).
2) Study of the sedimentation process after resuspension, using biosolids collected from Tank 1 (11 fish of 129.45 g and 2.03 kg m^{-3}).
3) Study of two consecutive processes of resuspension and sedimentation, using biosolids collected from Tank 1 (11 fish of 129.45 g and 2.03 kg m^{-3}).
4) Differences in the resuspension and sedimentation of biosolid wastes in different tanks (Tank 1 with 11 fish of 129.45 g and 2.03 kg m^{-3}, and Tank 2 with 69 fish of 79.54 g and 7.84 kg m^{-3}).

The results showed that the turbulence needed to resuspend biosolids increases with consolidation time (Figures 3 and 5, Article 4). For example, in Figure 3 (Article 4), it can be seen that an RMS_x of approximately 0.77 cm s^{-1} was needed to resuspend 50% of the biosolids after 1 h of consolidation, while an RMS_x of around 1.28 cm s^{-1} was needed to resuspend the same amount after 48 h of consolidation.

The turbulence was reduced after resuspension to evaluate sedimentation. We observed that the turbulence needed to maintain the same amount of biosolids in the water column had decreased (Figures 4, 5 and 6, Article 4), which shows that the presence of biosolids in the water column depends strongly on the initial state and is indicative of a counter-clockwise hysteresis loop. For example, an RMS_x of approximately 0.89 cm s^{-1} was needed to resuspend 75% of the biosolids from the bottom of the container (originated in Tank 1: Figure 4, Article 4), whereas only an RMS_x higher than 0.18 cm s^{-1} was needed for the same amount of biosolids to remain resuspended (in the water column).

When two consecutive processes of resuspension and sedimentation were evaluated, a lower percentage of biosolids remained resuspended during the second sedimentation at the same turbulence level used in the first. Figure 5 (Article 4) shows that more than 90% of the biosolids remained in the water column during the first sedimentation when an RMS_x of ~0.50 cm s^{-1} was applied. However, the percentage fell to 73% in the second sedimentation, which shows that higher turbulence was needed to maintain the same amount of biosolids in the water column when the resuspension and consolidation times were increased.

Finally, we detected differences in resuspension according to the fish size and density of the tanks in which the biosolids originated (Figure 6, Article 4). An RMS_x of 1.23 cm s^{-1} was needed to resuspend all of the biosolids from Tank 1 (2.03 kg m^{-3}, 129.45 g average weight), whereas the value was 0.89 cm s^{-1} for the biosolids from Tank 2, which contained smaller fish (7.84 kg m^{-3}, 79.54 g average weight). No differences were observed during the sedimentation process.

4. GENERAL DISCUSSION

4. GENERAL DISCUSSION

Flow pattern was analysed in rectangular tanks in which the water flowed from the upper to the lower end. We found that the velocity distribution depends strongly on the inlet configuration. Tests in a tank with a submerged horizontal inlet—a common configuration used in ongrowing farms—revealed a bypass current (short-circuiting) in which the inflow jet passed directly to the outflow, producing lateral eddies on both sides of the inflow. Low velocities were observed in the middle of these eddies, which facilitate the sedimentation of biosolids (Adamsson et al., 2003). Single upright waterfall configurations are also used frequently in ongrowing farms because the effect of the cascades increases the oxygen supply in the tank (Timmons and Youngs, 1991). We carried out experiments with this configuration and found that the flow pattern was highly heterogeneous. We also identified areas of recirculation containing dead volumes, the location of which varied over time. Despite these observations, it has long been assumed that rectangular tanks in which water flows from the upper to the lower end present plug-flow patterns (Watten and Beck, 1987; Watten and Johnson, 1990).

Heterogeneity decreased in a configuration with multiple upright waterfalls, and two different areas could be seen: an area of intense mixing close to the water inlet, followed by an area with a more homogeneous velocity field, characterised by a flow pattern very close to plug flow but with a steep velocity gradient from one side of the tank to the other. The conditions in the plug flow area became more homogeneous when the number of waterfalls was increased. Eddies at the water inlet produced water mixing and dissipated kinetic energy in the first section of the tank, which created a homogeneous flow pattern from the initial area of intense mixing to the outlet. Velocities were low despite the high degree of homogeneity, which can generate a gradient in dissolved oxygen and fish metabolites along the longitudinal axis (Young and Timmons, 1991). These conditions are also conducive to biosolids sedimentation. Westers and Pratt (1977) demonstrated that high water exchange rates are needed to produce self-cleaning action in raceways with plug-flow patterns. Nevertheless, plug flow is usually the desired pattern in raceways because the higher concentration at the water outlet facilitates the removal of fish metabolites and prevents internal recirculation (Timmons and Youngs, 1991). The distribution gradient of oxygen and metabolites can create uneven fish distribution (Burrows and Chenoweth, 1970) in the first section of the tank, where more oxygen is available (Ross and Watten, 1995; 1998).

Watten et al. (2000) first suggested creating a rotating-flow pattern in rectangular tanks, which they believed would combine the homogeneity and self-cleaning properties of circular tanks with the fish-handling advantages of rectangular tanks. The new tank configuration presents some kind of complexity of construction because four water inlets were needed for each rotating-flow cell.

In this dissertation, we demonstrated that a rotating-flow pattern can be produced by placing a single tangential inlet in one long side wall of a rectangular tank, which creates a rotating-flow cell for each water inlet.

We showed that, with identical inlet velocities and flow rates, the velocities in configurations in which water flows along the tank were lower than those obtained in tanks with a rotating-flow pattern, including both circular and rectangular tanks with rotating-flow cells. Ross and Watten (1998) found that the average velocities in circular tanks were an order of magnitude higher than those in plug-flow tanks with identical exchange rates (2.5 h^{-1}). In this study, we also observed that the average velocities in a configuration with rotating-flow cells were more than 10 times higher than those obtained in the plug-flow pattern area of the tank with multiple waterfalls. Higher velocities force fish to swim, which helps them to develop better muscle tone and flushes biosolids to the water outlet.

We carried out further experiments in tanks with length/width (*L/W*) cell ratios of 0.95, 1.43 and 1.91 to simplify and improve the design of tanks with rotating-flow cells. In addition, oblique baffles were placed in the walls to redirect the water current.

We defined a parameter called the tank resistance coefficient, C_t, to evaluate the resistance to water circulation produced by each configuration.

$$C_t = \frac{2Q(V_2 - V_1)}{AV_1^2} \qquad \textbf{Equation 5, Article 2}$$

where C_t is the tank resistance coefficient (dimensionless), Q is the flow rate, V_1 is the mean circulation velocity, V_2 is the water inlet velocity (jet velocity) and A is the wet area.

We showed that C_t can be used to determine the average velocities inside a tank (V_1) when the water exchange rate and water jet discharge velocity (V_2) are known:

$$V_1 \approx \left(\frac{2A_0}{AC_t}\right)^{1/2} V_2 \qquad \textbf{Equation 10, Article 2}$$

where A_0 is the total area of water inlet openings.

Average water velocities (V_1) are roughly proportional to water inlet velocities (V_2) for tanks with a specific discharge and water depth.

C_t was found to be a suitable parameter for evaluating the conditions in different types of tanks. The experiments showed that the values of C_t obtained in configurations with *L/W* ratios of 0.95 and 1.43 and baffles in one (0.09 for 0.95 and 1.43 *L/W* cell ratio) or both side walls (0.08 and 0.09 for 0.95 and 1.43 *L/W* cell ratios, respectively) were close to those obtained in a circular tank (0.08). Cell areas with a *L/W* ratio of 1.91 produced secondary eddies and C_t increased dramatically (0.18 and 0.17 with and without baffles, respectively); in addition, the main eddy core was displaced from the centre drain, so suspended biosolids could not be flushed and were more likely to settle on the tank bottom.

The results show that the *L/W* cell ratio has a direct impact on the flow pattern. Ratios of 0.95 and 1.43 produced no significant dead zones and increased the velocity around the water outlet when baffles were placed in the tank. The velocity increase is very important because higher velocities drag particles to the water outlet and produce self-cleaning conditions. Tvinnereim and Skybakmoen (1989) studied the flow pattern in a circular tank produced when water was injected with a slot inlet and also observed higher velocities around the water outlet. Davidson and Summerfelt (2004) studied the flow pattern in a Cornell-type dual-drain tank and found that the velocities close to the centre increased with higher bottom-centre flow rates, which produced a more uniform velocity profile.

Other authors reported that the mean circulation velocity (V_1) in circular flows shows a linear correlation with the jet velocity (V_2) (($V_1=\alpha V_2$), Paul et al., 1991). Timmons et al. (1998) recorded a value of α of between 0.15 and 0.20 for circular tanks. The equation proposed in this dissertation (Equation 5, Article 2) can be used to estimate α values according to the wet area (A), the total area of water inlet openings (A_0) and the tank resistance coefficient C_t:

$$\alpha=\left(\frac{2A_0}{AC_t}\right)^{1/2}$$ **Equation 4.1**

The ratio between V_1 and V_2 can only be used to evaluate a particular tank if the inlet jet diameter and wet area are kept constant.

After the publication of Article 2 of this dissertation, Labatut et al. (2007b) obtained an equation to predict water velocities in mean rotating-flow cells in rectangular tanks; they found that the average circulation velocities (V_1) are roughly proportional to water inlet velocity (V_2) in a tank with a given flow rate and water depth. Labatut et al. also observed a linear relationship between the mean water circulation velocity and the jet velocity, which is in agreement with Equation 4.2. This equation is based on the flux of momentum, which in turn derives from impulse force. However, the same authors also noted that the observed linearity implies that the water velocity magnitude is entirely dependent on the jet velocity, which was kept constant in their experiments.

$$U_{cell}=D_0U_o\sqrt{\frac{n_0\pi}{2D_{cell}h_{cell}}}$$ **Equation 4.2**

where U_{cell} is the mean water velocity, D_0 is the nozzle diameter, U_0 is the nozzle discharge velocity (jet velocity), n_0 is the number of nozzles, D_{cell} is the cell characteristic length (diameter) and h_{cell} is the height of the water column.

When comparing Equation 4.2 with the C_t equation (Equation 10, Article 2), we must take into account certain considerations. If we assume that $U_{cell}=V_1$, $U_0=V_2$, $D_{cell}=L=W$ (for a L/W cell ratio of 1), $h_{cell}=h$ (water depth) and $A_0=n_0\pi D_0^2/4$, the Labatut's equation would be equivalent to consider a too simple relationship between the tank resistance coefficient C_t and the geometrical parameters (L and h). If the relationship is:

$$D_0V_2\left(\frac{\pi n_0}{2AC_t}\right)^{1/2}=D_0V_2\left(\frac{\pi n_0}{2Lh}\right)^{1/2}$$, then

$C_t = \frac{Lh}{A}$, and with a wet area (for an intermediate cell in a rectangular tank) of $A = L^2 + 2Lh$

$$C_t = \frac{h}{L + 2h}$$ **Equation 4.3**

Considerations about equation presented by Labatut et al. (2007b) can to be pointed out:

- It assumes that the *L/W* cell ratio is equal to 1 in rotating-flow cells.
- It cannot be used to evaluate the influence of baffles.
- It cannot be used to evaluate the influence of the water inlet geometry.
- It does not take into account the influence of the tank size and therefore cannot be used to estimate the water resistance to flows.

Table 4.1 compares the velocities obtained in the experiments carried out for this dissertation (Articles 1 and 2) and by Watten et al. (2000) with those reported by Labatut et al. (2007b). The C_t values were calculated from experiments conducted by Watten et al. (2000) and Labatut et al. (2007b), and V_1/V_2 ratios are shown for all experiments.

C_t values were lower when baffles were used, which indicates lower resistance of water to flow and clearly illustrates the benefits of using baffles in rotating-flow cell tanks.

If we consider the C_t values obtained using the data from the three experiments conducted by Labatut et al. (2007b) in the same tank with different exchange rates ((5) in Table 4.1), we can see that the C_t parameter is not affected strongly by the flow rate used in any particular experiment. The C_t parameter is specific to each tank and can be used to predict velocities when different water inlet flow rates and velocities are applied.

If we compare the ratio V_1/V_2 with the ratios reported for circular tanks (0.15-0.20, Timmons et al., 1998), we can see that the V_1/V_2 values were always lower, even when a circular tank was used (0.058 in a 49-cm-diameter tank) ((3) in Table 4.1). The ratio V_1/V_2 varies only slightly when the water exchange rate is changed, as shown in the experiments conducted by Labatut et al. (2007b) ((5) in Table 4.1), where the water inlet flow rates were increased and V_2 was unchanged.

U_{cell} (Equation 4.2) can be used to predict the mean water velocity, but it does not reflect the velocity increase produced by the oblique baffles ((3) in Table 4.1, experiment with a *L/W* of 1.43) or the general improvement in the flow pattern.

Table 4.1: Average circulation velocities (V_1) and water inlet velocities (V_2), C_t calculated according to Equation 5 (Article 2), V_1/V_2 ratios, and U_{cell} calculated according to Labatut et al. (2007b). Tanks with rotating-flow pattern.

Ref	**Cell dimensions (m*m)**	h **(m)**	R **(h^{-1})**	**Entries per cell**	V_2 **(m s^{-1})**	V_1 **(ms^{-1})**	C_t	V_1/V_2	U_{cell} **(a)-(b) Equation 4.2**
(1)	6 cells 2.4*2.4	0.70	1.3	4	3.53	0.120	0.08	0.0340	0.077
(2)	2 cells 0.5*0.4 L/W=0.8	0.06	9.0	1	0.78	0.029	0.20	0.0371	0.044-0.039
(3)	6 cells 0.3*0.35 L/W=0.95	0.06	5.9	1 No B	0.30	0.017	0.14	0.0568	0.018-0.019
			5.9	1 B	0.59	0.030	0.09	0.0510	0.025-0.026
			5.9	2 B	0.59	0.032	0.08	0.0538	0.025-0.026
	4 cells 0.5*0.35 L/W=1.43	0.06	5.5	1 No B	0.44	0.020	0.13	0.0461	0.026-0.022
			5.5	1 B	0.44	0.026	0.09	0.0593	0.026-0.022
			4.9	2 B	0.39	0.022	0.09	0.0571	0.023-0.019
	3 cells 0.6*0.35 L/W=1.91	0.06	5.9	1 No B	0.64	0.023	0.18	0.0361	0.037-0.027
			5.9	1 B	0.64	0.024	0.17	0.0381	0.037-0.027
	Circular 49 cm	0.06	5.5	1	0.47	0.028	0.08	0.0580	0.024
(4)	3 cells 5.5*5.5	1.00	1.7	4	4.78	0.158	0.13	0.0331	0.156
(5)	3 cells 5.5*5.5	1.15	0.6	4	4.53	0.101	0.12	0.0223	0.092
			1.4		4.56	0.172	0.10	0.0377	0.139
			2.5		4.54	0.209	0.12	0.0460	0.185

(1) Watten et al. (2000): considering only velocities measured in the middle of the water depth.

(2) Present dissertation, Article 1: (a) considering rotating-flow cell width as D_{cell} ($W=D_{cell}$) and (b) considering rotating-flow cell length as D_{cell} ($L=D_{cell}$) in Equation 4.2.

(3) Present dissertation, Article 2: (a) considering rotating-flow cell width as D_{cell} ($W=D_{cell}$) and (b) considering rotating-flow cell length as D_{cell} ($L=D_{cell}$) in Equation 4.2.

No B: without baffles; 1 B: Baffles on one side wall; 2 B: Baffles on two side walls.

(4) Labatut et al. (2007a): considering only velocities measured in the middle of the water depth and 15% of bottom drainage.

(5) Labatut et al. (2007b): considering only velocities measured 5 cm from the tank bottom and 0% of bottom drainage.

U_{cell} gives a linear relationship between the mean circulation velocity (V_1) and the inlet velocity (V_2), but it only takes into account the nozzle diameter and water inlet velocity parameters; the results of the present study (Article 1, (2) in Table 4.1), particularly for experiments with two rotating-flow cells

(0.8 L/W cell ratio), show that C_t took a value of 0.20, which is higher than the values given in Article 2 ((3) in Table 4.1). It is obvious that C_t increased because only two rotating-flow cells were created and because the presence of a wall (high wet perimeter area) increased the fluid resistance to flow (lower values of V_1 were obtained). However, when U_{cell} was used to predict the mean circulation velocity, it gave a value 1.3 times greater than the measured velocity (V_1) ($U_{cell} \approx 4$ cm s^{-1}, compared to a measured value of 2.9 cm s^{-1}).

Equation 4.2, proposed by Labatut et al. (2007b), is only valid for a specific rectangular tank with rotating-flow cells and for specific conditions (V_2 constant); in contrast, C_t provided accurate predictions of circulation velocities for both rectangular tanks with rotating-flow cells, with or without baffles, and for circular tanks.

It is not easy to predict water velocities inside a tank, but it is very important for determining the desired velocities for different situations. We demonstrated that C_t is a suitable parameter for predicting water velocities in both circular and rectangular tanks with mixed rotating cell patterns. Control of velocities inside a tank provides an easy way to adjust them to fish species, fish length, and the velocity required to keep the tank bottom clean of biosolids, which consume oxygen and can produce hypoxic conditions.

High fish densities can create self-cleaning properties at lower velocities. Therefore, fish swimming activity can have a strong effect on self-cleaning properties, and it would be interesting to determine the extent of this effect in a specific tank with specific culture conditions.

Acoustic Doppler velocimetry (ADV) was used to quantify the turbulence generated by fish swimming activity (expressed as the root mean square of velocity, RMS). Laboratory tests with zebra fish (*Danio rerio*) showed that ADV can successfully detect and quantify the relationship between turbulence and fish density.

Separate tests in an ongrowing farm with sea bass *(Dicentrarchus labrax*) revealed differences in fish swimming patterns between the photophase (light period) and the scotophase (dark period). Fish were more active during the photophase, which is consistent with the behaviour described by other authors (Bégout Anras et al., 1997; Bégout Anras and Lagardère, 1998). We also found that light has a strong effect on fish swimming activity, which decreased when the lights were switched off. Eriksson (1978) suggested that light is the main environmental variable that affects rhythmic patterns in fish, which is confirmed by the results of this study.

We conducted tests with two fish densities and sizes (Experiment 1: 35.5 kg m^{-3} and 48 g; Experiment 2: 11.7 kg m^{-3} and 11.8 g) to determine the turbulence produced by fish swimming activity. It was demonstrated that turbulence is strongly linked to the level of fish swimming activity.

Data post-processing showed that data elimination was mainly due to COR filtering. More measurements were eliminated from Experiment 1 than from Experiment 2. This is probably because the larger fish size and higher density in the first experiment increased the likelihood that fish behaviour would disrupt the signal reception of the probe, thus leading to lower correlation. Further experiments should be conducted to determine the fish densities at which accurate velocity data can be obtained.

In a real rearing situation, the turbulence produced by fish swimming activity can be compared with the turbulence needed to resuspend biosolids from the tank bottom to determine the culture conditions that produce self-cleaning properties.

We used a vertically oscillating grid adapted to the specific characteristics of aquaculture biosolids to examine the turbulence needed to resuspend biosolids and to keep them in the water column. It was seen that higher turbulence was needed to resuspend biosolids once they had become consolidated. This increase in the resistance to resuspension is determined by particle size, consolidation and cohesiveness (Medina et al., 2001); aquaculture biosolids contain a high percentage of small particles and are mainly organic, which increases their cohesiveness (Chen et al., 1993).

Hysteresis behaviour was observed when we reduced the turbulence following resuspension to allow the biosolids to facilitate resedimentation. Hysteresis has been described in other cohesive sediments such as those produced in estuaries (Portela and Reis, 2004) or in snowmelt runoff streams (Langlois et al., 2005).

In aquaculture, it is beneficial to keep biosolids in the water column rather than allowing them to sink to the tank bottom, because settled biosolids are more difficult to resuspend and remove. If biosolids reach the tank bottom they can consolidate and accumulate, which leads to hypoxic conditions (Sumagaysay-Chavoso and San Diego-McGlone, 2003) and affects fish welfare and growth (Thetmeyer et al., 1999; Buentello et al., 2000). If biosolids are kept in the water column they can be removed by water recirculation (with lower turbulence than if they are on the tank bottom) and subsequently separated by filtration or sedimentation (Cripps and Bergheim, 2000).

Finally, we also observed differences in the turbulence needed to resuspend biosolids of different origin. Experiments carried out using the oscillating grid showed that higher turbulence was needed to resuspend biosolids in a tank with large fish (129.45 g) than in a tank with small fish (79.54 g), which could be due to the fact that larger fish produce bigger faecal particles (Magill et al., 2006).

The turbulence obtained under the effect of the oscillating grid can be compared with previous values recorded in the ongrowing farm to determine the self-cleaning capacity of the tank.

The ongrowing farm experiments were conducted with an average velocity of approximately 13 cm s^{-1} and with densities of 35.5 kg m^{-3} in Experiment 1 and 11.7 kg m^{-3} in Experiment 2. The values of *RMS* generated by fish swimming activity were of the same order of magnitude (Experiment 1: 3.632 cm s^{-1} during the photophase and 2.248 cm s^{-1} during the scotophase; Experiment 2: 1.728 cm s^{-1} during the photophase and 1.419 cm s^{-1} during the scotophase) as those needed to resuspend biosolids (1.23 and 0.89 cm s^{-1}). The turbulence produced by fish swimming activity (measured with ADV) was higher than that needed to resuspend biosolids (measured with the oscillating grid), which confirms that the turbulence produced by the water current and fish swimming activity in the tank would be sufficient to maintain self-cleaning conditions.

Taken together, the results of the experiments in this dissertation show that it is essential to possess accurate knowledge of the flow patterns in aquaculture tanks in order to define a configuration that creates the optimal conditions and water velocities for promoting fish health and producing self-cleaning properties. If a rectangular tank with water flowing along the tank from the upper to the lower end is used, the best choice is the configuration with multiple upright waterfalls, which produced an area of intense mixing close to the inlet followed by a homogeneous velocity field. A rectangular tank with a rotating-flow pattern is also a good configuration because it creates a more uniform flow pattern and higher velocities, although it is also more difficult to design and construct.

If a rectangular tank with a rotating-flow pattern is used, the L/W cell ratios should be lower than 1.43. A L/W cell ratio of 1.91 is unsuitable for rotating-flow cells because it produces secondary eddies and dead zones that reduce the efficiency of the water use. The configuration is easier to construct if a L/W cell ratio of 1.43 is used, because fewer water inlets per tank are needed than when a ratio of 0.95 is used. It is highly recommendable to use baffles to redirect the water because they also increase the velocities around the water outlet, which produces more homogeneous conditions and self-cleaning properties.

The tank resistance coefficient C_t can be used to predict the water velocity in rotating-flow patterns and is a suitable parameter for evaluating the resistance to circulation. C_t can also be used to determine the optimal circulation velocities in a tank, which are then produced by adjusting the water exchange rate and the water inlet velocity.

Finally, the turbulence generated by fish swimming activity has a strong effect on the tank hydrodynamics and the biosolids dynamics. This effect was quantified using ADV techniques.

To evaluate the turbulence needed to resuspend biosolids in an aquaculture tank, a method was proposed in which an oscillating grid is used to adjust the turbulence at the biosolids level.

Further research should be carried out to take into account the interaction between flow pattern and fish activity, which is important in determining the conditions needed to produce self-cleaning properties in an aquaculture tank.

5. GENERAL CONCLUSIONS

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The design criteria of aquaculture tanks, the turbulence needed to resuspend biosolids, and the turbulence produced by fish swimming activity were examined to determine the conditions for optimal fish rearing and rapid removal of biosolids.

The conclusions are presented in the order stated in the objectives.

The influence of the geometry and water inlet devices on the flow pattern of the most common aquaculture tanks will be analysed to define design criteria that will improve rearing conditions and optimise the use of water.

Analysis of tank hydrodynamics using PTV demonstrated that the flow pattern is strongly influenced by the water inlet and outlet characteristics. In addition, different configurations showed considerable variations in water mixing and the distribution of velocities along the tank.

The configuration with a single horizontal inlet in a rectangular tank showed a bypass current. A single upright waterfall was used to increase the mixing, but dead volumes were observed in the centre of the tank; the position of these eddies was shown to be strongly time-dependent.

The configuration with multiple upright waterfalls showed an area of intense mixing close to the water inlet; beyond this area, we observed a pattern similar to plug flow in an area with more homogeneous conditions.

The highest velocities and homogeneities in the rectangular tanks were reached when tangential inlets were placed in the centre of the longer side to create a rotating-flow pattern. This configuration combines the ease of handling of rectangular tanks with the homogeneous flow pattern, higher velocities and self-cleaning properties of circular tanks.

Design criteria will be established for 'rotating-cell rectangular aquaculture tanks', which combine the advantages of rectangular and circular tanks.

It was proved that L/W cell ratios greater than 1 produce a rotating-flow pattern in rectangular tanks. L/W cell ratios of 1.43 reduced the number of water inlets required and did not have a significant effect on the flow pattern, the water velocities inside the tank or the dead volumes.

A L/W cell ratio of 1.91 is not recommended because it led to the appearance of dead volumes and reduced the circulating water velocities dramatically.

Baffles to drive the water current were placed between two water inlets in one of the side walls. This new configuration improved the flow pattern considerably and increased the water velocities, particularly around the outlets, which helped to flush out the biosolids. The flow pattern did not improve further when baffles were placed in two side walls.

The tank resistance coefficient (C_t) was shown to be a useful parameter for evaluating tanks with rotating-flow patterns (rectangular and circular). When the C_t value for a specific tank is known, it is easier to determine the optimal velocities for maintaining fish health, muscle tone and respiration, and for producing self-cleaning properties.

A method for studying fish activity by measuring the turbulence generated by swimming will be developed. This will provide a means of analysing the relationship between the turbulence produced by fish swimming activity and the rearing conditions in the tank.

ADV is a simple and fast technique for measuring the turbulence generated by the swimming activity of large numbers of fish. We showed that turbulence is closely linked to the level of fish swimming activity and fish density.

The proposed method revealed that the swimming activity of sea bass is related to the photoperiod, and the results were consistent with observations in the literature. The method presented here would be very useful for studying fish activity under different environmental conditions (temperature, concentration of dissolved oxygen, etc.).

The turbulence needed to resuspend aquaculture biosolids and to keep them suspended in the water column will be analysed using a vertically oscillating grid adapted to the specific characteristics of aquaculture biosolids.

The oscillating grid method can be adapted to study resuspension and sedimentation processes of biosolid wastes originated in aquaculture tanks, which are characterised by high cohesiveness and low specific gravity.

The proposed method demonstrated hysteresis behaviour in resuspension-sedimentation cycles. We found that lower turbulence was required to keep biosolids in the water column when the solids originated in the column itself rather than the tank bottom.

The turbulence required to resuspend biosolids from the tank bottom was higher during the second resuspension. The resistance increased with consolidation time. We also found that different degrees of turbulence were needed to resuspend biosolids of different origins.

Rearing conditions in aquaculture tanks can be evaluated by comparing the turbulence needed to keep biosolids in the water column with the turbulence produced by fish swimming activity. This information can then be used to maintain self-cleaning conditions.

Self-cleaning properties are vital in aquaculture tanks due to the difficulty of resuspending biosolids for removal once sedimentation has occurred. In addition, sediment that remains on the tank bottom for a long time becomes increasingly harder to remove and develops greater resistance to subsequent sedimentation-resuspension processes.

The following recommendations for future research are based on the results of the different experiments carried out in the preparation of this dissertation:

-Different water inlet configurations (single or double inlet, shape of water inlet, direction of water, etc.) should be tested to determine their effect on the tank resistance coefficient. Research should also be carried out with large tanks to evaluate the scale effect on C_t.

-Further experiments should set fish density limits to improve the efficiency of ADV techniques used to measure the turbulence caused by fish swimming activity.

-*RMS* was used here as a single indicator of the turbulence exerted on sediments. However, future research should take into account the interaction between water velocity and turbulence and the resulting effect on biosolid resuspension.

-Research should also be carried out on the effect of feed binders on the turbulence needed to prevent sedimentation or resuspension of faeces; the results will indicate the efficiency of binders in preventing the disintegration of biosolids.

6. REFERENCES

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7. ABSTRACT

7. ABSTRACT (English)

The purpose of this work is to characterise the hydrodynamics of the most commonly used aquaculture tanks and to define design criteria that will improve self-cleaning properties and optimise the use of space and water. The dissertation is submitted as a compilation of individual articles. Two of the articles focus on the hydrodynamic characteristics of various tank geometries with different water inlet designs. The remaining articles examine the turbulence required for sedimentation and resuspension of biosolids generated in aquaculture tanks. The turbulence values obtained are compared with the turbulence generated by fish swimming activity in aquaculture tanks.

Hydrodynamic characteristics were studied in the laboratory by applying particle-tracking velocimetry techniques to scale models. The turbulence generated by fish swimming activity was studied using acoustic velocimetry techniques and quantified using the root mean square (*RMS*) of velocities. Finally, the turbulence needed to resuspend biosolids was determined using an oscillating grid adapted to the specific characteristics of the aquaculture biosolids (high organic content and high cohesiveness); *RMS* was also used to quantify the turbulence needed to resuspend biosolids.

Analysis of the hydrodynamic characteristics of scale models revealed that the flow pattern is strongly affected by the water inlet design. The flow pattern was homogeneous in configurations in which water flowed along the tank from the upper to the lower end, and dead zones and bypass currents were frequently observed. Flow velocities were low. The homogeneous flow pattern and higher water velocities were observed when water was injected tangentially to create a rotating flow pattern. Rotating flow cells produced a circular flow pattern in rectangular tanks. We defined a tank resistance coefficient (C_t), which was found to be suitable for evaluating both circular and rectangular tanks with rotating flow patterns. The coefficient was used to assess the effect of baffles and various length/width cell ratios. We found that baffles increased the water velocity at the outlets, which is important in the removal of biosolids and for producing self-cleaning properties.

Acoustic velocimetry was used to study fish swimming activity. We found that the turbulence generated by swimming activity increases with density and that the photoperiod has a strong effect on the swimming activity of sea bass.

Finally, an oscillating grid was used to determine the turbulence needed to resuspend biosolids and the turbulence needed to keep them in the water column; these experiments illustrated the effect of consolidation time on the turbulence required for resuspension. Hysteresis was observed when turbulence was reduced to evaluate sedimentation following resuspension, and different levels of turbulence were required for resuspension in different tanks (with different densities and fish sizes).

7. RESUMEN (Castellano)

El propósito del presente trabajo es caracterizar hidrodinámicamente los tanques más utilizados en acuicultura y dar pautas de diseño para mejorar su autolimpieza, y optimizar la eficiencia de utilización tanto del espacio como del agua. La tesis se presenta en forma de compendio de artículos. En los dos primeros se estudiaron las características hidrodinámicas de diferentes configuraciones geométricas y diferentes diseños de entrada de agua. En los dos últimos artículos se estudiaron los procesos de sedimentación y resuspensión de los biosólidos que se generan en los tanques acuícolas, midiendo la turbulencia necesaria tanto para la sedimentación como para la resuspensión, y se compararon los valores obtenidos con los de la turbulencia generada por la propia actividad natatoria de los peces en los tanques de cultivo.

El estudio de las características hidrodinámicas de los tanques se realizó con modelos a escala en laboratorio, que se evaluaron mediante velocimetría de seguimiento de partículas. La turbulencia generada por los peces al nadar se estudió mediante velocimetría acústica, siendo la media cuadrática de las velocidades (*Root Mean Square RMS*) el parámetro utilizado para cuantificar la turbulencia. Finalmente, la turbulencia necesaria para la resuspensión de biosólidos se determinó mediante una parrilla oscilante adaptada a las características de dichos biosólidos (alto contenido orgánico y alta cohesividad); el *RMS* también fue el parámetro utilizado para cuantificar la turbulencia necesaria para la sedimentación y resuspensión de biosólidos.

En el estudio de las características hidrodinámicas de los modelos a escala, se ha determinado que el patrón de flujo está fuertemente condicionado por el diseño de entrada del agua. Se ha observado que en las configuraciones en que el agua fluyó des de un extremo del tanque al otro, el patrón de flujo fue heterogéneo con presencia frecuente de zonas muertas y corrientes de corto circuito. Las velocidades alcanzadas fueron bajas. Se consiguieron velocidades más altas y una mayor homogeneidad cuando el agua se introdujo tangencialmente a la pared del tanque para crear células de mezcla. Las células de mezcla presentaron un flujo típico de tanques circulares a pesar de la geometría rectangular del tanque. Se definió el parámetro coeficiente de resistencia de tanque (C_t), que ha demostrado ser válido para evaluar tanques tanto circulares como rectangulares con células de mezcla. Dicho coeficiente ha sido útil para poder evaluar el efecto del emplazamiento de bafles y de las diferentes ratios entre longitud y ancho de célula estudiadas. Se ha comprobado que el efecto de los bafles aumenta las velocidades en la salida del agua. El aumento de estas velocidades permitirá eliminar los biosólidos del tanque y alcanzar una mejor autolimpieza.

Referente al estudio de la actividad natatoria de los peces mediante velocimetría acústica, el método propuesto ha permitido determinar que la turbulencia generada por los peces al nadar aumenta con la densidad, así como el fuerte efecto que tiene el fotoperíodo en la actividad natatoria de las lubinas.

Por último, el uso de la parrilla oscilante para determinar el nivel de turbulencia necesario para resuspender biosólidos y el nivel necesario para mantenerlos en la columna de agua, ha permitido determinar el efecto del tiempo de consolidación en la turbulencia necesaria para la resuspensión. También se ha observado la existencia de histéresis cuando después de un proceso de resuspensión, la turbulencia se disminuyó para evaluar el proceso de sedimentación. Finalmente, se han podido determinar diferencias en la turbulencia necesaria para la resuspensión cuando se evaluaron biosólidos procedentes de diferentes tanques, con diferentes densidades de cultivo y talla de peces.

7. RESUM (Català)

El propòsit del treball es caracteritzar hidrodinàmicament els tancs més utilitzats en el sector aqüícola, i donar pautes de disseny per millorar-ne l'autoneteja, i optimitzar l'eficiència d'utilització tant de l'espai com de l'aigua. La tesis es presenta en forma de compendi d'articles. En els dos primers s'estudien les característiques hidrodinàmiques de diferents configuracions geomètriques i diferents dissenys d'entrada d'aigua. En els dos últims s'estudien els processos de sedimentació i resuspenció dels biosolids que es generen en els tanc aqüícoles, mesurant la turbulència necessària per la sedimentació i resuspenció, i posteriorment es varen comparar els valors obtinguts amb els de la turbulència generada per la pròpia activitat natatòria del peixos en els tancs de cultiu.

L'estudi de les característiques hidrodinàmiques dels tancs, es va realitzar amb models a escala al laboratori, que es van evaluar mitjançant velocimetria de seguiment de partícules. La turbulència generada pels peixos al nedar es va estudiar mitjançant velocimetria acústica, utilitzat la mitja quadràtica de les velocitats (*Root Mean Square RMS*) com a paràmetre per quantificar la turbulència. Finalment, la turbulència necessària per la resuspenció de biosolids es va determinar amb una graella oscil·lant adaptada a les característiques dels biosolids aqüícoles (alt contingut orgànic, i alta cohesivitat); l'*RMS* també fou el paràmetre utilitzat per quantificar la turbulència necessària per la resuspenció de biosolids.

Amb l'estudi de les característiques hidrodinàmiques dels models a escala, s'ha determinat que el patró de flux està fortament condicionat pel disseny de l'entrada d'aigua. S'ha observat que en les configuracions on l'aigua fluïa de d'un extrem del tanc a l'altre, el patró de flux era molt heterogeni amb presència freqüent de zones mortes i corrents de curt-circuit. Les velocitats aconseguides foren baixes. Es van aconseguir velocitats més altes i una major homogeneïtat quan es va introduïr l'aigua tangencialment a la paret del tanc per tal de crear cèl·lules de barreja. Les cèl·lules de barreja van presentar un flux típic de tancs circulars tot i la geometria rectangular dels tancs utilitzats. Es va definir el paràmetre coeficient de resistència de tanc (C_t), que ha demostrat ser vàlid per evaluar tancs tant circulars com rectangulars amb cèl·lules de barreja. Aquest coeficient ha estat útil per evaluar l'efecte de l'emplaçament de bafles i de les diferents ratios entre longitud i amplada de cèl·lula estudiades. S'ha comprovat que l'efecte dels bafles augmenta les velocitats a la sortida de l'aigua. L'augment d'aquestes velocitats permetrà eliminar els biosòlids del tanc i aconseguir una millor autoneteja.

Referent a l'estudi de l'activitat natatòria dels peixos mitjançant velocimetria acústica, el mètode proposat ha permès determinar que la turbulència generada pels peixos al nedar augmenta amb la densitat, així com l'important efecte que té el fotoperíode en l'activitat natatòria dels llobarros.

Per últim, la utilització de la graella oscil·lant per determinar el nivell de turbulència necessari per resuspendre els biosolids i el nivell necessari per mantenir-los a la columna d'aigua, ha permès determinar l'efecte del temps de consolidació en la turbulència necessària per la resuspenció. També s'ha observat que existeix histèresis quan després d'un procés de resuspenció, la turbulència es va disminuir per evaluar el procés de sedimentació. Finalment, s'han pogut determinar diferències en la turbulència necessària per la resuspenció quan es van evaluar biosolids procedents de diferents tancs, amb diferents densitats de cultiu i talla de peixos.

Agraïments

Agraïments

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