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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.

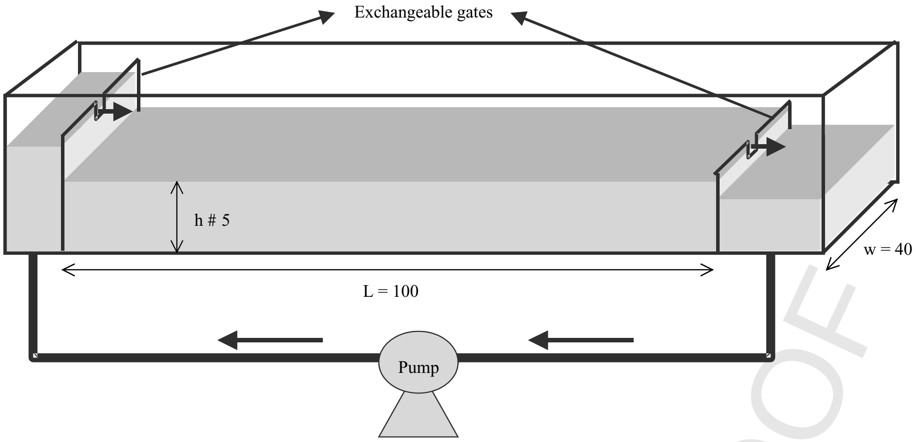

Fig. 1. Recirculating water system and dimensions of the tank.

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).

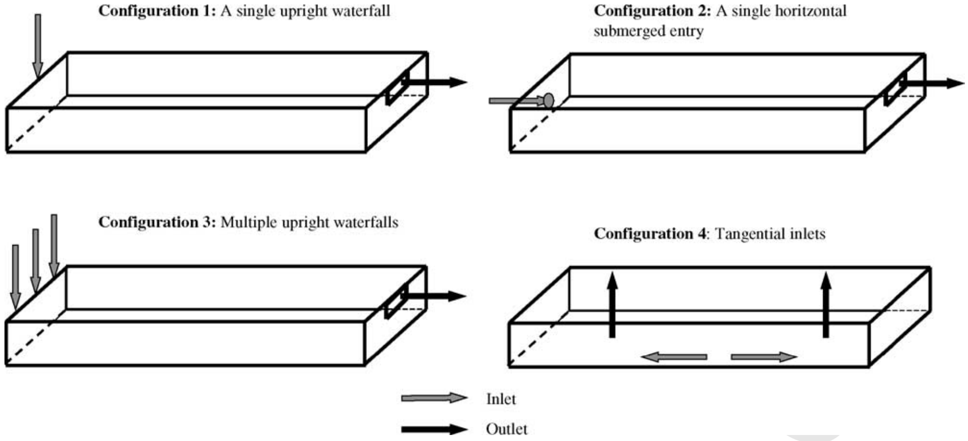

Fig. 2. Tank configurations analysed.

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 two 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

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

	Distance between inlets (cm)	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	3.8h 2.5h	182	5.5	–	9.1	2.5
Tangential inlets	–	215	6.0	77.5	9.0	–

exchange rate scale λ_e must be $\lambda_e = \lambda_L^{-0.5}$. Thus, an exchange rate $9\,h^{-1}$ in the analysed 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

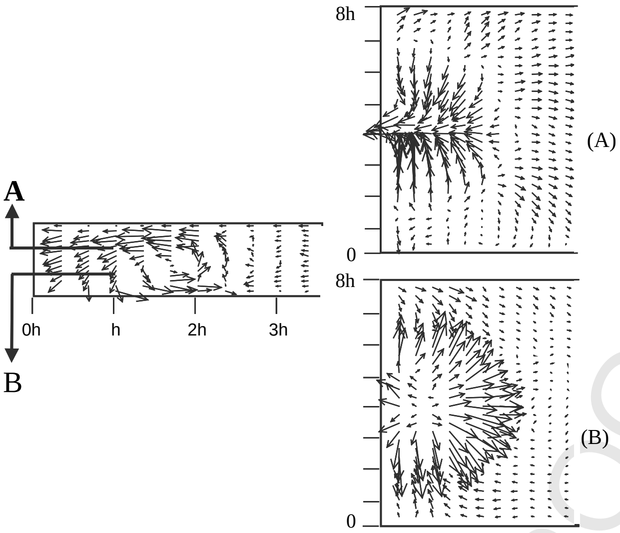

Fig. 3. Velocity fields in a vertical section taken in front the single waterfall (left) and in the two horizontal sections A and B (right).

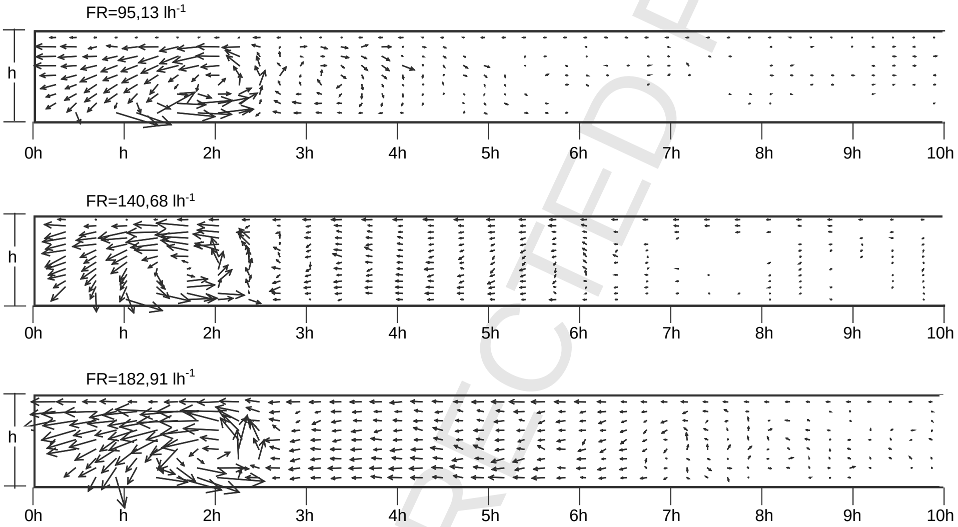

Fig. 4. Velocity fields in vertical sections of the first half of the tank with configuration 1, using different flow rates.

these large eddies, the velocity field is very heterogeneous and the internal recirculation in the tank is very important.

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

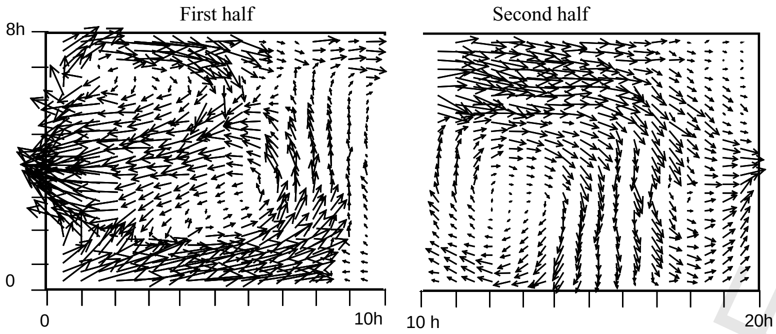

Fig. 5. Velocity fields in horizontal sections with configuration 1.

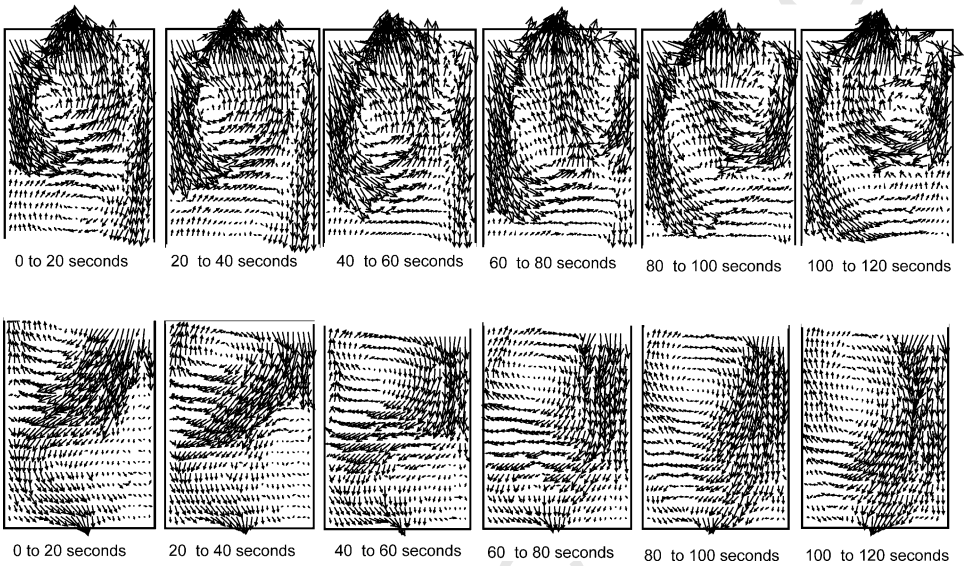

Fig. 6. Sequence of flow pattern observed along 2 min with configuration 1.

kind of configuration must be highlighted. Eddies are continuously changing their shape and emplacement.

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

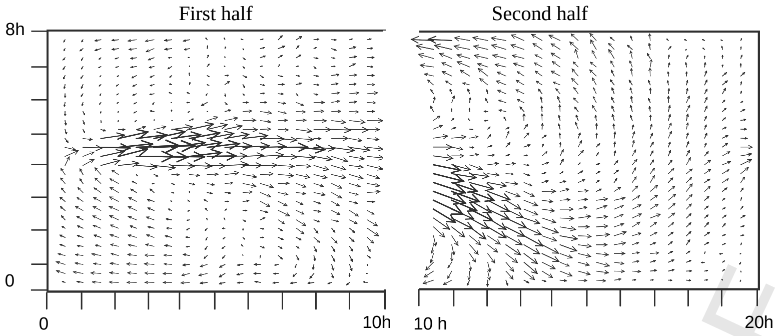

Fig. 7. Velocity fields in horizontal sections with configuration 2.

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 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

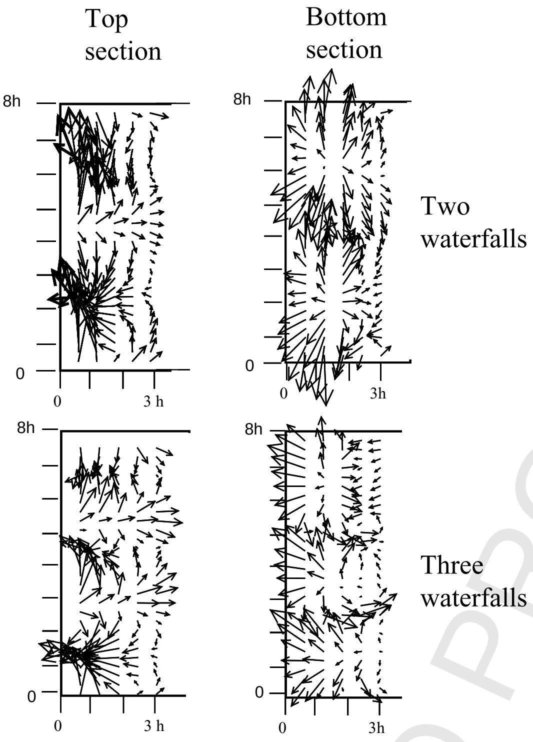

Fig. 8. Velocity fields in horizontal sections taken close to the inlet in configuration 3, with two and three waterfalls.

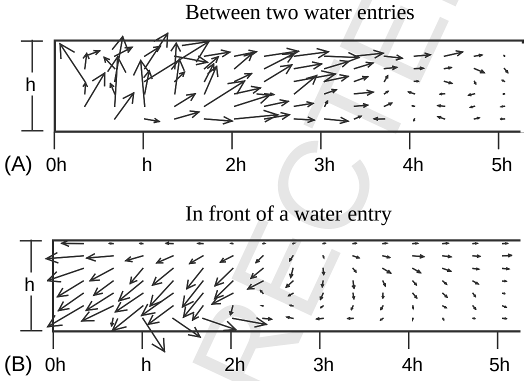

Fig. 9. Velocity fields in vertical sections in configuration 3. The first taken (A) between two water entries and (B) the second in front of water entry.

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.

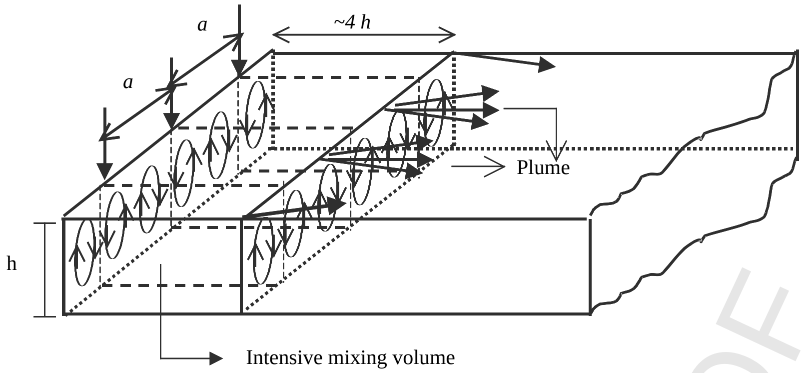

Fig. 10. Flow behaviour in a configuration with multiple waterfalls when the distance between eddies is around 2.5 times the water depth.

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.

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

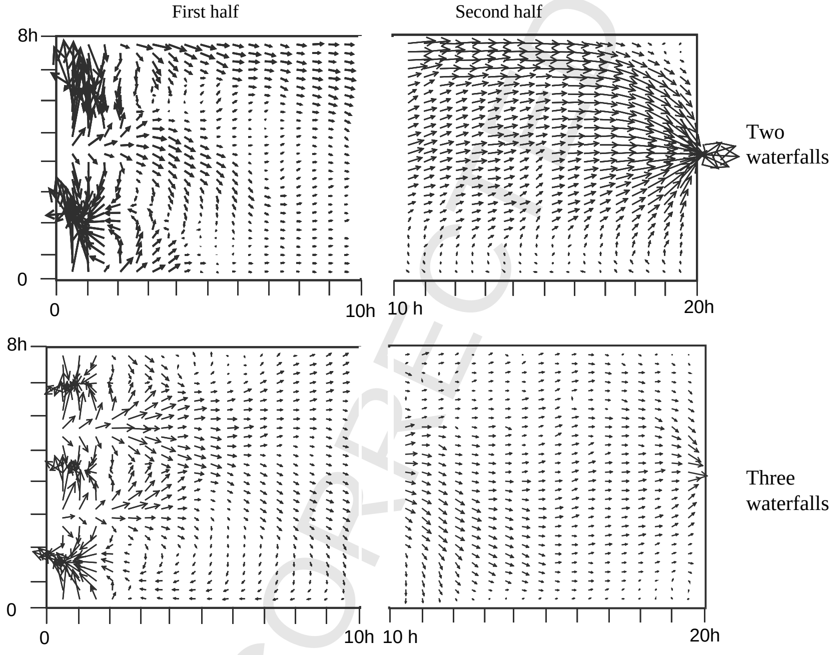

Fig. 11. Field velocities in horizontal sections of configuration 3 with two and three waterfalls.

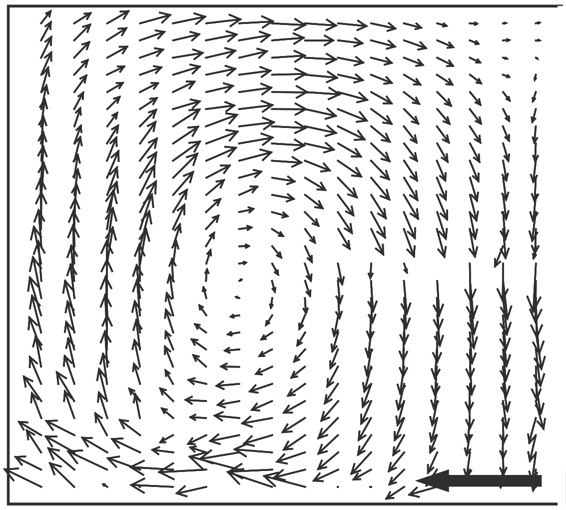

Fig. 12. Field velocities in a horizontal section of one of the tank halves with configuration 4.

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.

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

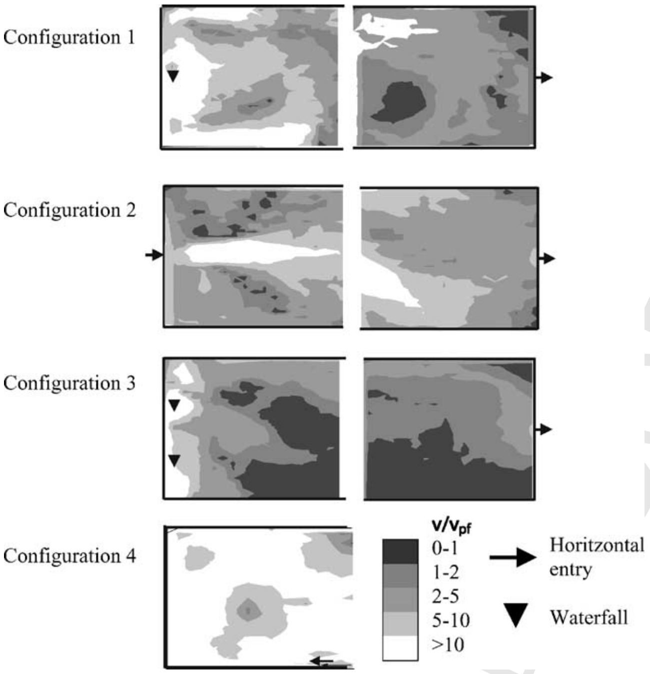

Fig. 13. Spatial distribution of the non-dimensional velocity (v/v_{pf}) in the horizontal section of the four analysed configurations.

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.

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

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

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.

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.

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