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# Flow pattern in aquaculture circular tanks: Influence of flow rate, water depth, and water inlet & outlet features

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### ABSTRACT

Circular tank geometry is very common in aquaculture because it provides more stable flow patterns, a more homogeneous distribution of dissolved oxygen and metabolites and better self cleaning features. Many works were performed in the last years to determine optimal velocities for maintaining general fish health, but the distribution of velocities inside circular tanks is frequently very heterogeneous. This work is focused on the analysis of the influence of design parameters in the distribution of water velocities inside aquaculture circular tanks. A model is proposed to estimate the distribution of velocities by determining the angular momentum per unit mass next to the tank wall and around the central axis. The model depends on the water inflow and outflow rates, the water inlet velocity, the tank radius, the water depth, and three tank-specific parameters which must be determined experimentally to include the effect of the wall roughness, the characteristics of water inlet devices and the presence of singular elements in the tank bottom producing friction losses.

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## 1. Introduction

Optimum hydrodynamic conditions in aquaculture tanks are determined by species requirements and waste elimination. The main design parameters that influence tank hydrodynamics, including flow pattern and average velocities, are the geometry and the water inlet and outlet characteristics (Klapisis and Burley, 1984; Tvinnereim and Skybakmoen, 1989; Timmons et al., 1998; Oca et al., 2004; Masaló, 2008).

Circular tanks, with a tangential inlet and the outlet placed in the central bottom, are one of the most common configurations used in aquaculture. This tank geometry allows obtaining more stable flow patterns and higher velocities than rectangular tanks, thanks to the rotating characteristics of the flow (Ross and Watten, 1998; Oca and Masaló, 2007a). This results in a more homogeneous distribution of dissolved oxygen and metabolites, and facilitates the elimination of biosolids from the tank bottom.

The main factors affecting the average velocity in circular tanks have been analyzed by several authors. Tvinnereim and Skybakmoen (1989) pointed out that water velocity in a circular tank with tangential water entry is controlled by the inlet impulse force (Eq. (1)).

$$F_i = \rho Q (V_{in} - V_1) \quad (1)$$

where  $\rho$  is the water density,  $Q$  the injected water flow rate, and  $V_{in}$  and  $V_1$  the jet inlet velocity and the circulating velocity of water in the tank, respectively.

Oca and Masaló (2007a) defined a non dimensional tank resistance coefficient ( $C_t$ ) (Eq. (2)) which allows estimating average velocities ( $V_{avg}$ ) inside a tank as a function of flow rate ( $Q$ ) and water inlet velocity ( $V_{in}$ ), assuming  $V_{in} \gg V_{avg}$ .

$$C_t = \frac{2QV_{in}}{AV_{avg}^2} \quad (2)$$

where  $A$  is the wet area.

$C_t$  is suitable not only for adjusting the average velocities of a specific tank to the self-cleaning tank requirements and desired fish swimming speed, but also to compare the energy required by different flow rotating tank designs to achieve a specific average velocity.

In addition to the average velocity, the distribution of velocities is important. Many authors proposed optimal velocities for fish health and growth (p.e.: Timmons and Youngs, 1991; Losordo and Westers, 1994; Castro et al., 2011, for salmonids; Bengtson et al., 2004, for Summer flounder *Paralichthys dentatus*; Merino et al., 2007, for California halibut *Paralichthys californicus*). At swimming speeds lower than optimal, a substantial amount of energy is lost due to higher spontaneous activity (e.g., aggression), while at speeds higher than optimal, swimming becomes unsustainable, stressful, and the ensuing anaerobic metabolism will increase lactate levels, create an oxygen debt and finally cause fatigue (reviewed by Davidson (1997) and Palstra and Planas (2011)).

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Nevertheless, the appliance of these recommendations is hindered by the heterogeneity of velocities in circular tanks. A high heterogeneity leads to a less efficient use of the space available, due to the fish tendency to avoid tank volumes with too high velocities and dead volumes with lower DO and higher metabolites concentrations (Ross et al., 1995; Duarte et al., 2011; Almansa et al., 2012). In this way, a distribution uniformity coefficient has been proposed by Oca and Masaló (2007b) and Masaló and Oca (2010) to measure the homogeneity of velocities in the tank. The analysis of this uniformity requires not only a global assessment of the average velocity in the tank but also a detailed flow pattern analysis to determine the influence of the different design parameters in the homogeneity of velocities inside the tank.

Davidson and Summerfelt (2004) described the flow pattern in specific designs of circular tanks and compared the velocity profiles in a dual drain tank with most of the water exiting the tank through the side-wall, and a small rate (0–12%) through the tank bottom. The velocities near the tank center clearly increased with increasing the bottom flow drain.

In the field of water treatment processes, a relatively similar flow can be observed in vortex settling basins. The hydrodynamics of these basins have been widely studied (Mashauri, 1986; Paul et al., 1991; Fisher and Flack, 2002; Veerapen et al., 2005; Yunjie, 2009), but it must be pointed out the high differences existing with circular aquaculture tanks in the magnitude of important design parameters, like the retention time or the relationship between water inlet velocity and average velocity, which is much higher in aquaculture tanks.

The aim of the present work is to analyze, in aquaculture circular tanks, the influence of tank characteristics (diameter, water height, roughness) and water inlet and outlet features (flow rates, impulse forces) in the distribution of water velocities inside the tank.

## 2. Materials and methods

### 2.1. Theoretical background

The most typical configuration of aquaculture circular tanks consists in a tangential water entry placed next to the tank wall and a water outlet placed in the tank bottom center. There exist some configurations where water outlet flow is divided in two fractions, the first leaving the tank through the bottom center outlet and the second through the water wall.

Water entering tangentially into the tank, combined with the water outflow through the tank center, produces a rotating movement of the water around the tank center, that is, a vortex. In a general way, we can differentiate between the “forced vortex” (or rotational vortex), with velocity increasing proportionally to the radius, and the “free vortex” (or irrotational vortex), where the speed and rotation rate of the fluid are largest at the center and decrease progressively with distance from the center.

The forced vortex occurs can be obtained in a liquid occupying a vessel by spinning the recipient or by applying a torque to force the liquid to rotate like a solid body. The typical example of a free vortex is the rotating flow that occurs in a vessel when the liquid is drained through a hole in the bottom.

In a forced vortex, the tangential velocity along a streamline ( $V$ ) can be expressed as

$$V = \omega r \quad (\omega = \text{constant}) \quad (3)$$

where  $\omega$  is the angular velocity; and  $r$  is the radius.

We can define the angular momentum per unit mass ( $\beta$ ) in a vortex point placed at a radius  $r$  as

$$\beta = Vr \quad (4)$$

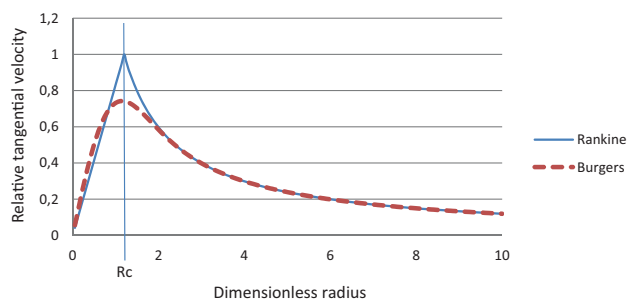


Fig. 1. Distribution of velocities obtained with the Rankine combined vortex model (continuous line) and with the Burgers model (dashed line).

Observing Eqs. (3) and (4) it can be seen that, in the forced vortex, the angular momentum per unit mass increases proportionally to the squared radius.

In contrast, in the free vortex no torque is applied and there is no energy consumption from an external source. According with the second Newton's law, when no torque is applied in an inviscid fluid the value of  $\beta$  must be identical for any radius and therefore the tangential velocity along any streamline must be inversely proportional to the radius ( $r$ ) of the streamline.

$$V = \frac{C}{r} \quad (5)$$

where  $C$  is a constant value which can be determined from a known value of  $V$  in a radius  $r$ .

Eq. (5) implies that the tangential velocity at the rotation axis is infinite. This kind of flow pattern does not occur in physical fluids. The existence of viscosity results in friction losses, proportional to squared velocities, which are not negligible near the rotation axis. Some models have been proposed to describe the distribution of tangential velocities in the core of a free vortex. The Rankine combined vortex (Lugt, 1983) is a simple model where tangential velocities increase linearly from the rotation axis up to a maximum value at a radius  $R_c$ , and decrease from this point outward proportional to the inverse of radius (see Fig. 1). The Burger's vortex model (Burgers, 1948) gives a distribution of tangential velocities following the mathematical form

$$V = \frac{C}{r} (1 - e^{-ar^2/2\nu}) \quad (6)$$

where  $\nu$  is the kinematic viscosity and  $a$  is the strength of suction.

#### 2.1.1. Influence of water inlet velocity and flow rate in the flow pattern

In aquaculture circular tanks, water entering tangentially to the tank wall at a velocity  $V_{in}$  larger than the mean circulating velocity in the tank  $V_1$  provides an impulse force  $F_i$  (Eq. (1)) and a torque  $T_i$  which can be calculated as

$$T_i = F_i R = R \rho Q (V_{in} - V_1) \quad (7)$$

$R$  being the tank radius.

Considering that, in aquaculture tanks, the water inlet velocity  $V_{in}$  is much higher than  $V_1$ , Eqs. (1) and (7) can be replaced by

$$F_i \cong \rho Q V_{in} \quad (8)$$

$$T_i = F_i R \cong R \rho Q V_{in} \quad (9)$$

In terms of momentum conservation, the total external torque acting on the system must be zero, and therefore  $T_i$  must be equal to the resistance torque  $T_r$  due to the boundary shear forces from the tank surfaces.

The resistance torque due to the boundary friction force from the tank wall  $T_{rw}$  can be estimated as

$$T_{rw} = \tau_0 A_{wall} R = \tau_0 H 2\pi R^2 \quad (10)$$

Being  $A_{wall}$  the tank wall area,  $H$  the water height and  $\tau_0$  the average boundary shear stress, which here will be considered uniform in all the wall area.

Assuming a turbulent regime and taking  $V_w$  as the water velocity in the wall,  $\tau_0$  can be expressed as

$$\tau_0 = \frac{1}{8} f \rho V_w^2 \quad (11)$$

where  $f$  is Darcy–Weisbach friction factor, which for turbulent rough flow depends only on the relative roughness (Franzini and Finnemore, 2001).

If we estimate the water velocity in the tank wall  $V_w$  by balancing  $T_i$  (Eq. (9)) and  $T_{rw}$  (Eqs. (10) and (11)) we obtain

$$V_w = \sqrt{\frac{4}{\pi \rho f} R} \sqrt{\frac{Fi}{H}} \quad (12)$$

The angular momentum per unit mass next to the tank wall  $\beta_w$  will be

$$\beta_w = \sqrt{\frac{4R}{\pi \rho f}} \sqrt{\frac{Fi}{H}} \quad (13)$$

The resistant torque due to the boundary force from the tank bottom  $T_{rb}$  should be calculated by integrating the resistance of each infinitesimal ring strip with width  $dr$  within the tank bottom (Eq. (14)).

$$T_{rb} = \int_0^R \tau_0 2\pi r^2 dr = \int_0^R \frac{1}{4} f \rho \pi r^2 V^2 dr \quad (14)$$

If a forced vortex pattern were assumed, with the water rotating like a solid body,  $V$  could be replaced by  $\omega r$  with constant  $\omega$ , and  $T_{rb}$  would become  $T_{rw} R / (5H)$ . Nevertheless, this assumption is inaccurate in this kind of tank, and the low viscosity of water can make the influence of  $T_{rb}$  in  $V_w$  negligible. Therefore, the balance done in Eq. (12) can be a good approach to estimate  $V_w$ .

### 2.1.2. Influence of water outlet flow rate in the flow pattern

The water outlet placed in the center of the circular aquaculture tanks promotes the creation of a free vortex with the tangential velocities distribution described above. The strength of the free vortex will be related to the flow rate drained through the central outlet. Kawakubo et al. (1978) observed that the formation of a vortex around a sink requires a discharge flow rate exceeding a threshold value.

Some authors analyzed the flow that occurs when a fluid drains out of a container. They found a complex flow structure when vertical velocities and radial velocities were considered. They described a bottom boundary layer with an inward flow toward the drain and an upwelling flow next to the central region with axial velocities depending linearly on height (Andersen et al., 2006; Lundgren, 1985; Huang et al., 2008; Yukimoto et al., 2010). These radial and axial flows have a great importance in the study of vortex separators to remove solids from wastewater or in the study of atmospheric phenomena like tornados.

The velocity component which will have a significant influence in fish swimming and behavior inside an aquaculture tank will be the tangential velocity ( $V$ ), which was found to be almost independent of height except in the boundary layer near to solid boundaries (Andersen et al., 2006; Despres, 2007; Mashauri, 1986). Nevertheless, the relative importance of the volume flux in the boundary layer can influence the distribution of velocities inside the tank. Mashauri (1986), for a vortex settling basin, defined two

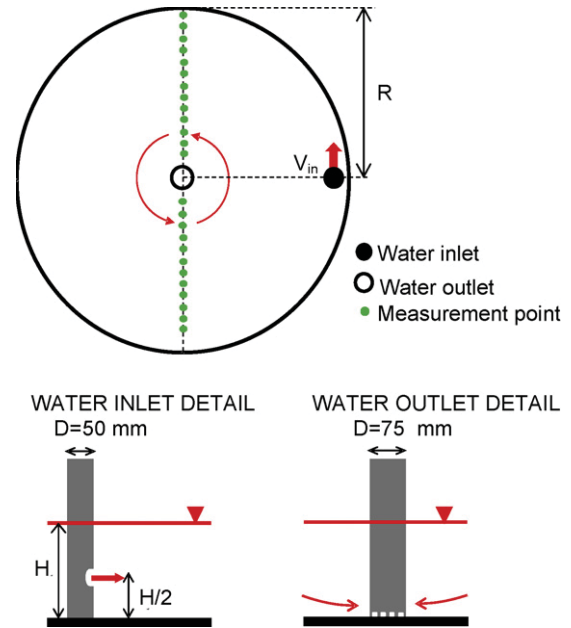


Fig. 2. Experimental setup.

vortex volumes: a free vortex zone for radius lower than  $R/3$ , and a forced vortex zone where radius is higher than  $R/3$ . In the free vortex zone ( $\beta = \text{constant}$ ), the tangential velocity was calculated using Eq. (5), with  $C$  proportional to  $Q$ , while in the forced vortex zone ( $\beta = Vr = \omega r^2$ ) angular velocity  $\omega$  was constant and tangential velocity was calculated using Eq. (3).

Yukimoto et al. (2010), working with a bathtub vortex in a cylindrical tank rotating at a constant angular velocity  $\Omega$ , reported that two regimes of vortices can occur in the steady-state depending on  $\Omega$  and the volume flux  $Q$  through the drain hole: when  $Q$  is large and  $\Omega$  is small (regime I), a potential vortex is formed in which angular momentum outside the vortex core is constant in the non-rotating frame, verifying Eqs. (4) and (5). However, when  $Q$  is small or  $\Omega$  is large (regime II), almost all of the radial volume flux occurs only in the boundary layer and the angular momentum decreases with decreasing radius. In similar conditions, Andersen et al. (2006) showed that in the bulk of the fluid, far above the boundary layer and outside the central region, the measured tangential velocities are modeled well by the line vortex  $V = Q/\pi \delta r$ . Here,  $\delta$  is the thickness of the boundary layer, which increases when  $\Omega$  decreases.

Summarizing, two simultaneous phenomena take place in aquaculture tanks: The first, next to the tank wall, due to the higher water inlet velocity  $V_{in}$  which provides an angular momentum to the fluid next to the tank wall ( $\beta_w$ ). The second, around the central axis, due to the water flow rate exiting the tank through the central outlet ( $Q$ ) which tends to maintain a constant angular momentum ( $\beta_0$ ) because of the formation of a free vortex in absence of torque. The transition from  $\beta_w$  to  $\beta_0$  will be determined by the radial volume flux in the bulk of the fluid and by friction losses.

### 2.2. Experimental tests

Experiments were carried out in a cylindrical tank with flat bottom and 1.5 m diameter. Water inlet was tangential to the wall and water outlet was placed at the bottom center, in the way shown in Fig. 2.

The steps followed in the experimental test were (1) measuring tangential velocities along the tank diametrical axis at half water depth, with different flow rates, water inlet velocities (by changing inlet diameters) and tank water heights, (2) analyzing the variation

**Table 1**

Water inlet velocity ( $V_{in}$ ), flow rate ( $Q$ ), impulse force ( $F_i$ ) and water depth ( $H$ ) for each tank configuration.

Tank configuration	$V_{in}$ (m/s)	$Q$ (l/h)	$F_i$ (N)	$H$ (m)
$Q=600 - F_i=0.35 - H=0.5$	2.0	600	0.35	0.5
$Q=900 - F_i=0.75 - H=0.5$	3.1	900	0.75	0.5
$Q=1200 - F_i=1.41 - H=0.5$	4.0	1200	1.41	0.5
$Q=1200 - F_i=0.44 - H=0.5$	1.3	1200	0.44	0.5
$Q=2200 - F_i=1.47 - H=0.5$	2.5	2200	1.47	0.5
$Q=2700 - F_i=1.48 - H=0.5$	2.0	2700	1.48	0.5
$Q=600 - F_i=0.35 - H=0.2$	2.0	600	0.35	0.2
$Q=900 - F_i=0.75 - H=0.2$	3.1	900	0.75	0.2
$Q=1200 - F_i=0.44 - H=0.2$	1.3	1200	0.44	0.2
$Q=2200 - F_i=1.47 - H=0.2$	2.5	2200	1.47	0.2

of the angular momentum per unit mass ( $\beta$ ) along the tank radius, and (3) estimating the values of  $\beta$  next to the tank wall ( $\beta_w$ ) and around the central axis of the tank ( $\beta_0$ ).

Tangential velocities were taken using an Acoustic Doppler Velocimeter ADV (Nortek 10 MHz velocimeter). ADV sensor is a high-precision instrument that measures all three flow velocity components in the sampling volume placed 5 cm below the probe. Data obtained was post-processed using the package WinADV (Wahl, 2000). Correlation coefficient (COR) above 70, and signal-to-noise ratio (SNR) above 5 were used. A more detailed description about post-processing can be found in Masaló et al. (2008). Each measurement lasted 2 min, with readings taken every 0.04 s. The average of the 3000 values obtained provided the time-averaged velocity for each point. One measurement every 5 cm was taken along the diametrical axis at half water depth for each tank configuration.

The tank configurations analyzed are shown in Table 1. Two water depths (0.2 and 0.5 m) were tested, with flow rates ranging from 600 to 2700 l/h and impulse forces  $F_i$  (Eq. (8)) from 0.35 to 1.48 N.

### 3. Results and discussion

#### 3.1. Velocity profiles

The velocity profile along a diametrical axis is shown in Fig. 3. Some observations to be done from the figure are:

- (1) Velocities always decrease from the outer wall to the center, achieving a minimal value at an intermediate radius and

increasing again toward the center of the tank. Only in the tests performed with the lower flow rates, decreasing velocities with wall distance can also be observed in the central volume.

- (2) The slope of the velocity profile seems to continuously increase with the radius, with negative values in the central volume and the maximal values next to the wall. This behavior is far away from the model proposed by Mashauri (1986), especially for distances to the center higher than  $R/3$ .
- (3) The vortex core, with tangential velocities increasing linearly with radius from zero to a maximum value, has a very small radius and cannot be detected in our experiments  $R_c < 6$  cm)
- (4) For each water depth, velocities close to the wall increase with  $F_i$ . In contrast, close to the tank center the velocity increases with the flow rate.
- (5) For similar  $F_i$  values, velocities close to the wall are much higher with the lower water depth (0.2 m) than with the higher one (0.5 m). This different behavior is not observed close to the tank center.
- (6) A slight asymmetry can be observed between both tank halves. They must be attributed to the position of the two monitored radius relative to the water inlet jet (see Fig. 2). Nevertheless, the differences have been considered small enough to analyze the flow assuming identical velocity profiles for any tank radius.

#### 3.2. Distribution of $\beta$

Fig. 4 shows the distributions of  $\beta$  versus radius, showing that the angular momentum per unit mass is always higher close to the wall, where the water inlet provides an additional angular momentum, than close to the center, where the angular momentum is mainly determined by the outlet flow rate. The relationship between  $\beta$  and  $r$  values fits very well to an exponential curve

$$\beta = c e^{kr} \quad (15)$$

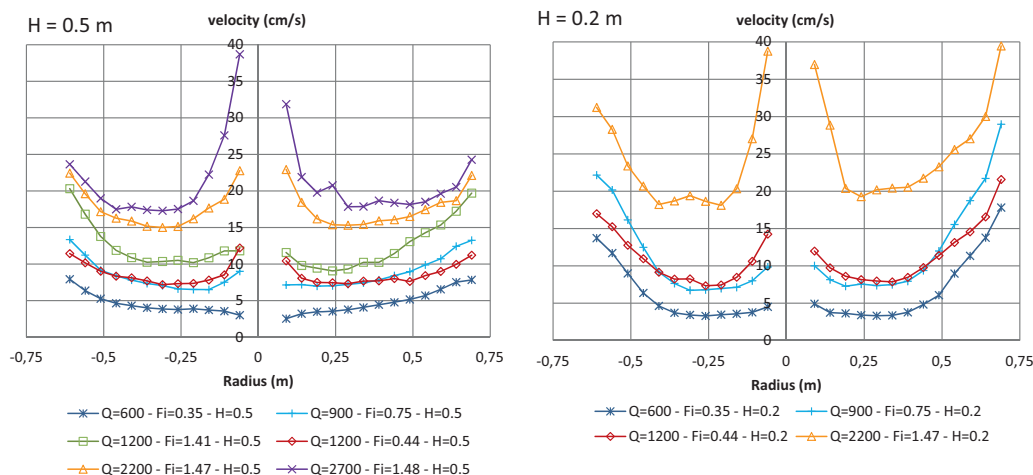
indicating a closely exponential decrease of  $\beta$ , from the wall to the center of the tank.

If the effect of the vortex core were neglected, the value of  $\beta$  in the tank center ( $\beta_0$ ) would be obtained by taking  $r=0$ :

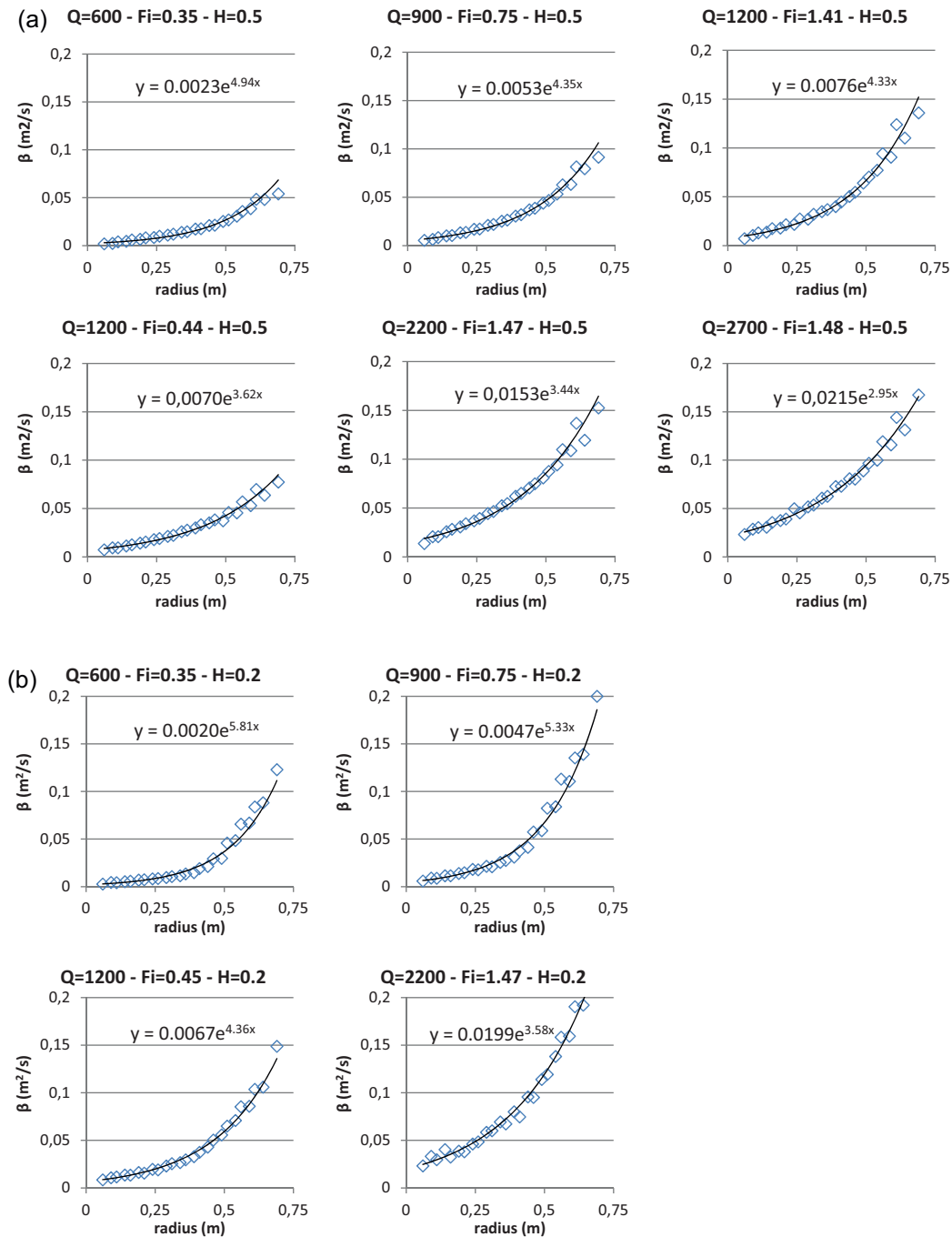
$$\beta_0 = c \quad (16)$$

and the expected values of  $\beta$  near the tank wall ( $\beta_w$ ) can be obtained taking  $r=R$ .

$$\beta_w = \beta_0 e^{kR} \quad (17)$$



**Fig. 3.** Velocity profiles in the diametrical axis with different tank configurations (left: 0.5 m water depth, and right: 0.2 m water depth).  $Q$  = flow rate expressed in l/h and  $F_i$  = water inlet impulse force expressed in N.



**Fig. 4.** (a) Angular momentum per unit mass ( $\beta$ ) versus radius (configurations with water depth = 0.5 m). (b) Angular momentum per unit mass ( $\beta$ ) versus radius (configurations with water depth = 0.2 m).

The values of  $\beta_0$  ( $c$ ) and  $k$  can be obtained by linear regression between  $\ln(\beta)$  and  $r$  for each tank configuration (Eq. (18)) and  $\beta_w$  calculated through Eq. (17). The results are summarized in Table 2, including the coefficient of determination  $R^2$  of the linear regression.

$$\ln(\beta) = \ln(c) + k r \quad (18)$$

For a specific tank with radius  $R$  and a constant friction factor  $f$ , if we assume the torque balance which leads to Eq. (13), the angular momentum per unit mass next to the tank wall ( $\beta_w$ ) should be proportional to  $(Fi/H)^{0.5}$ . Fig. 5 shows the relationship between both

**Table 2**

Values of  $k$ ,  $\beta_0$  and  $\beta_w$  for each tank configuration, and coefficient of determination  $R^2$  for the linear regressions between  $\ln(\beta)$  and  $r$ .

Tank configuration	$k$ (m <sup>-1</sup> )	$\beta_0$ (m <sup>2</sup> /s)	$\beta_w$ (m <sup>2</sup> /s)	$R^2$
Q=600 - Fi=0.35 - H=0.5	4.94	0.0023	0.0877	0.967
Q=900 - Fi=0.75 - H=0.5	4.35	0.0053	0.1322	0.987
Q=1200 - Fi=1.41 - H=0.5	4.33	0.0076	0.1889	0.984
Q=1200 - Fi=0.44 - H=0.5	3.62	0.0070	0.1018	0.987
Q=2200 - Fi=1.47 - H=0.5	3.44	0.0153	0.1955	0.981
Q=2700 - Fi=1.48 - H=0.5	2.96	0.0215	0.1923	0.991
Q=600 - Fi=0.35 - H=0.2	5.81	0.0020	0.1491	0.980
Q=900 - Fi=0.75 - H=0.2	5.34	0.0047	0.2428	0.987
Q=1200 - Fi=0.45 - H=0.2	4.36	0.0067	0.1691	0.993
Q=2200 - Fi=1.47 - H=0.2	3.58	0.0199	0.2821	0.984

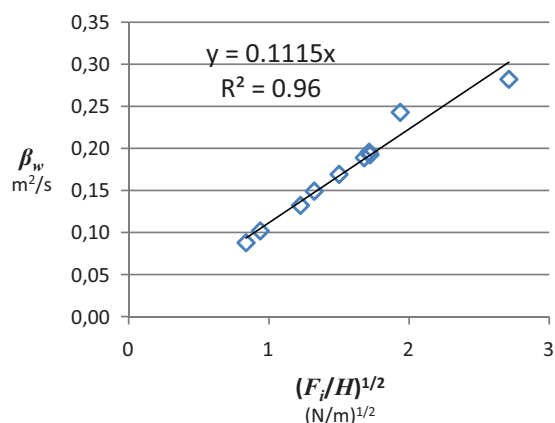


Fig. 5. Angular momentum per unit mass next to the tank wall  $\beta_w$  versus  $(F_i/H)^{1/2}$ .

parameters for the experimental tank used in our work, which takes the form:

$$\beta_w = m \sqrt{\frac{F_i}{H}} \quad (19)$$

being, in the experimental tank,  $m = 0.1115 \text{ m}^2 \text{ kg}^{-1/2}$  and with  $R^2 = 0.96$ .

The angular momentum per unit mass near the tank center for the analyzed configurations can be related with the outlet flow rate. Fig. 6 shows the relationship between  $\beta_0$  and  $Q$ . It can be seen that the relationship fits very well to a linear regression. The tendency line crosses the  $Q$  axis at a positive value. This behavior is in agreement with the results obtained by Kawakubo et al. (1978), who observed that the formation of a vortex around a sink requires a discharge flow rate exceeding a threshold value. The result of the regression leads, in our experimental tank, to an expression like:

$$\beta_0 = nQ - p \quad (20)$$

which can also be expressed as

$$\beta_0 = n(Q - Q_0) \quad (21)$$

where  $Q_0 = p/n$ , and represents the threshold value of  $Q$  needed for the formation of the central vortex.

In the experimental tank analyzed, the values obtained were  $n = 34.272 \text{ m}^{-1}$ ,  $p = 0.0038 \text{ m}^2/\text{s}$  and  $Q_0 = 0.000111 \text{ m}^3/\text{s}$  (400 l/h), with  $R^2 = 0.97$ .

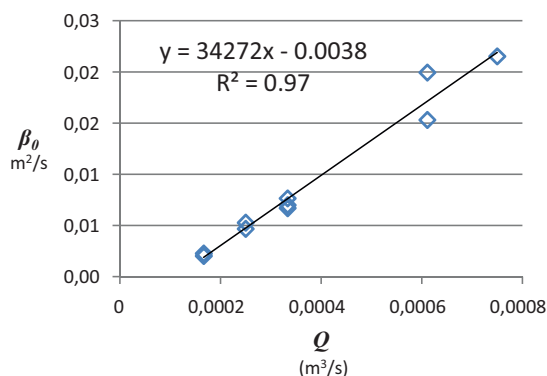


Fig. 6. Angular momentum per unit mass in the central tank axis  $\beta_0$  versus water outlet flow rate  $Q$ .

The estimation of  $\beta$  for any radius can be made after from the values of  $\beta_0$  and  $\beta_w$ . From Eq. (17), the value of  $k$  can be related with  $R$ ,  $b_0$  as:

$$k = \frac{1}{R} \ln \left( \frac{\beta_w}{\beta_0} \right) \quad (22)$$

Replacing  $k$  in Eq. (15) or (18) leads to Eqs. (23) and (24) which allow calculating  $\beta$  and  $V$  for any radius as a function of  $r$ ,  $\beta_0$  and  $\beta_w$ :

$$\beta = \beta_0^{1-r/R} \beta_w^{r/R} \quad (23)$$

$$V = \frac{1}{r} \beta_0^{1-r/R} \beta_w^{r/R} \quad (24)$$

Eq. (24) allows simulating the distribution of velocities in a tank radius, for specific values of  $Q$ ,  $F_i$  and  $H$ , by estimating  $\beta_w$  and  $\beta_0$  from Eqs. (19) and (20), respectively, after determining the values of coefficients  $n$ ,  $p$  and  $m$  for a specific tank. The comparison between simulation and experimental values for the analyzed tank is shown in Fig. 7.

### 3.3. Experimental determination of tuning parameters for a specific tank

As shown above, tangential velocities in a specific tank depend on geometric factors and operational conditions. The geometric factors are wall roughness, tank radius, characteristics of water inlet devices, and the presence of singular elements in the tank bottom producing friction losses. Operational conditions are the water flow rate ( $Q$ ), inlet velocity ( $V_{in}$ ), and depth ( $H$ ). While operational conditions are easily adjustable, geometrical factors are permanent. A few measurements allow determining experimentally the corresponding tuning parameters  $m$ ,  $n$  and  $p$  for a specific tank, which reflect the influence of these factors and, in practice, determine the flow for any operational conditions.

The tuning parameter  $m$  allows determining the values of  $\beta_w$  as a function of the water depth ( $H$ ) and the water inlet velocity and flow rate ( $V_{in}$  and  $Q_{in}$ ). The value of  $m$  will be related to the tank radius and wall roughness (Eq. (12)), and will be nearly constant if the two main conditions above explained are verified: (1)  $V_{in}$  much higher than the mean circulating velocity in the tank and (2) Darcy–Weisbach friction factor ( $f$ ) depending only on the relative roughness, which implies turbulent rough flow.

The adjustment parameters  $n$  and  $p$  allow setting the values of  $\beta_0$  for different water outlet flow rates ( $Q$ ). Also tank radius and bottom roughness are expected to modify the values of  $n$  and  $p$  by affecting the fraction of radial volume flux occurring in the boundary layer and in the bulk of fluid. Moreover, it must be noted the existence of a threshold flow rate value ( $Q_0$ ) needed for the formation of the central vortex. The use of lower flow rates in the experimental determination of the tuning parameters will lead to inaccurate results.

Assuming these constraints, it is easy to set the mentioned tuning parameters for a tank with specific roughness and radius by:

- (1) Measuring the velocities at different distances from the center (e.g.  $r = 0.25R$ ,  $0.5R$ , and  $0.75R$ ) with known values of  $V_{in}$ ,  $Q$  and  $H$ .
- (2) Calculating  $\beta$  values for each radius ( $\beta = Vr$ ).
- (3) Obtaining the values of  $\beta_0$  and  $\beta_w$  by linear regression between  $\ln(\beta)$  and  $r$  (Eq. (18)).
- (4) Obtaining the value of  $m$  by linear regression between  $\beta_w$  and  $\sqrt{F_i/H}$  (Eq. (19)).
- (5) Obtaining the values of  $n$  and  $p$  or  $Q_0$  by linear regression between  $\beta_w$  and  $Q$  (Eq. (21)).

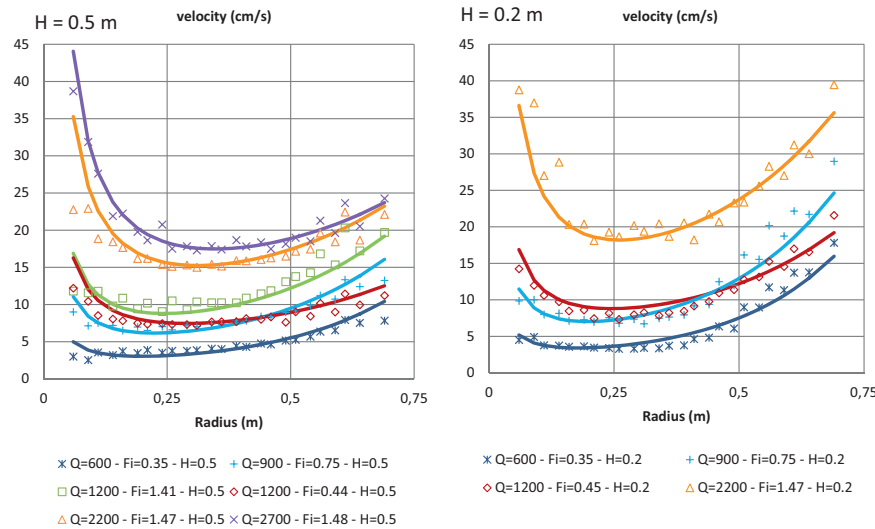


Fig. 7. Modelled (lines) and measured (points) tangential velocities along the tank radius for each tank configuration.

This procedure will allow predicting tangential velocities profiles in the tank for different flow rates, water inlet diameters and water height. These parameters can be fit to obtain optimal velocities in fish culture tanks and appropriated speed uniformity.

The influence of fish density in the distribution of velocities inside the tank has not been still analyzed. New experiments are being conducted to establish the importance of this factor in the velocity profile obtained for usual fish culture conditions.

#### 4. Conclusions

The velocity profiles in a diametrical axis of a circular aquaculture tank with a tangential water entry and a bottom central outlet has been analyzed by trying different flow rates, water inlet velocities and water heights.

In all the tank configurations, the distributions of the angular momentum ( $\beta = Vr$ ) versus radius fits very well to an exponential curve  $\beta = c e^{kr}$ .

For a specific tank with radius  $R$  and a constant friction factor  $f$ , the angular momentum per unit mass next to the tank wall ( $\beta_w$ ) has been found to be proportional to  $(Fi/H)^{0.5}$ .

Around the central axis of the tank, a linear relationship has been found between the angular momentum per unit mass ( $\beta_0$ ) and the flow rate ( $Q$ ). The existence of a threshold value  $Q_0$  needed for the formation of the central free vortex has been also confirmed.

The estimation of the flow speed  $V$  for any radius can be made as a function of the  $\beta_0$  and  $\beta_w$  by taking  $V = 1/r \beta_0^{1-r/R} \beta_w^{r/R}$ .

The geometrical factors which ultimately determine the flow pattern are the wall roughness, the tank radius, the water height, the characteristics of water inlet devices and the presence of singular elements in the tank bottom producing friction losses. These factors determine the values of three tuning parameters which in eventually determine the values of  $\beta_w$  and  $\beta_0$ . A procedure has been proposed to determine the tuning parameters for a given tank geometry.

The proposed model allows fitting the flow rate, water inlet diameter and water height to obtain optimal velocities and proper speed uniformity in aquaculture tanks.

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