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

Joan Oca*, Ingrid Masalo

Departament d'Enginyeria Agroalimentària i Biotecnologia, Universitat Politècnica de Catalunya, BARCELONATECH C/Esteve Terrades 8, 08860 Castelldefels, Spain

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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 loses.

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 (Klapsis 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)).

$$F_i = \rho Q\,(V_{\text{in}} - V_1) \tag{1}$$

where ρ 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 (Ct) (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 $V_{\text{in}} \gg V_{\text{avg}}$.

$$Ct = \frac{2QV_{\text{in}}}{AV_{\text{avg}}^2} \tag{2}$$

where A is the wet area.

Ct 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)).

* Corresponding author. Tel.: +34 935521223; fax: +34 935521001.
E-mail address: joan.oca@upc.edu (J. Oca).

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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

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

where ω is the angular velocity; and r is the radius.

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

$$\beta = Vr \tag{4}$$

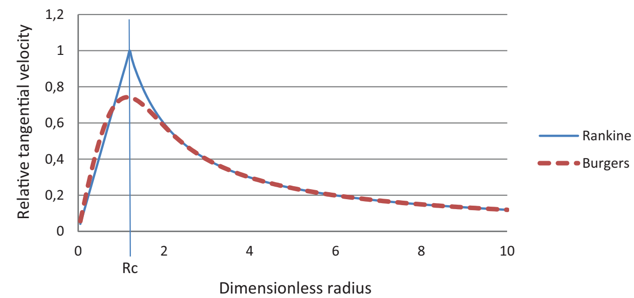

Fig. 1. Distribution of velocities obtained with the Rankine combined vortex model (continuous line) and with the Burgers model (dashed line).

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 β 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.

$$V = \frac{C}{r} \tag{5}$$

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 loses, 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 Rc, 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

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

where ν 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

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

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

$$F_i \cong \rho Q V_{in} \tag{8}$$

$$T_i = F_i R \cong R\rho\ Q V_{in} \tag{9}$$

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.