NUMERICAL SIMULATION OF HYDRODYNAMICS IN A RECONFIGURED FARMING TANK

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Abstract. This study analyzed and evaluated the hydrodynamics parameters of a new aquaculture tank resulting of a modified mixed-cell raceway (MCR) combined to a Burrows tank by using the CFD tool Ansys Fluent. The numerical investigation included modeling water velocities, calculating the HRT (Hydraulic retention time) and analyzing the tank power requirements. Predicted water velocities ranged between 3 and 40 cm/s which is suitable for fish farming. The study also indicated that the calculated HRT was 46 minutes and the power requirement was nearly 6 W/m^3. These results are acceptable for aquaculture and provide a good mixing capacity, a self-cleaning and also a rapid effluents discharge. This study highlights the importance of inlets and outlets configuration including jet velocity and nozzle diameter in tank hydrodynamics.

Key words: Aquaculture, CFD, Farming tank, Modeling, Ansys Fluent

1. INTRODUCTION

Aquaculture is the fastest growing animal production, global aquaculture production reaching 130.9 million tons in 2022; it was the first time in history that aquaculture production surpassed fisheries production (FAO, 2024). Several studies have been realized to improve aquaculture systems and production. Nowadays, numerical simulations are used, more often in aquaculture engineering, creating "smart aquaculture". Indeed, modeling could help in reducing experimental procedures, operational costs and increasing efficiency and profitability. CFD (Computational Fluid Dynamics) is widely used in modeling aquaculture tanks by studying water velocities and temperature (Montas *et al.*, 2000; Veerapen *et al.*, 2005). This technique is based on solving mass, momentum and energy equations (Ferziger *et al.*, 2002). Fredriksson *et al.* (2008) used the numerical tool Ansys Fluent™ based on the finites elements method to model sea cages hydrodynamics by solving the Navier-Stokes equations and using the turbulence model K-ε. The authors found that waves force must be considered in farming enclosures conceptions; they also proved that separated cages act like individual enclosures (Fredriksson *et al.*, 2008). Dionne (2012) used an implemented model in Ansys Fluent to study a modified Gilbert tank; the studied modifications would help fast cleaning and fish feces elimination. Predicted results provided a 54% evacuation of effluents. Zhang *et al.* (2022) used the turbulence model K-ε and the finite volume discretization implemented in Ansys Fluent to study the effect of different spatial utilization in a single channel RAS (Recirculation Aquaculture System) on tank hydrodynamics. The results were validated against *in-situ* velocity measurements. The authors depicted that the fillet radius is an important parameter in farming design since it influences the dead volumes creation and flow characteristics (Zhang *et al.*, 2022).

Choi *et al.* (2023) used the numerical tool Ansys 2021 to investigate hydrodynamic and thermal characteristics of 5 aquaculture tanks. Results showed that the circular tanks mixed better than the octagonal tanks and that changing the inlet and outlet water position, dimensions, and the number, can improve the flow uniformity, mixing characteristics, dissolved oxygen distribution and self-cleaning ability (Choi *et al.*, 2023). Liu *et al.* (2023) studied the hydrodynamics of a dual-channel rectangular circular-angle culture tank, using the finite volume method to solve the three-dimensional Navier–Stokes equation and the RNG k–ε turbulence model equation to simulate the relative inflow distance, and the results were validated by comparison with experimental results of a physical model. They found that the velocity distribution uniformity at the bottom of the tank, as well as the kinetic energy gradient and uniformity of flow, were impacted by the relative inflow distance (Liu *et al.*, 2023). Zhang *et al.* (2023) used a numerical model (the Euler–Lagrange method, combined with the discrete phase model and the RNG k-ε turbulence model) to assess the hydrodynamics and self-cleaning characteristics of square tanks by changing the number of water inlets, and results were validated against experimental tests. Results showed that steady injection increased flow uniformity and energy utilization, and the hydraulic mixing uniformity and effective energy utilization are improved by reducing the number of inlet pipes (Zhang *et al.*, 2023).

Farming tank design is important for the fish performance as well as the system costs (Burrows and Chenoweth, 1970). The Mixed-cell Raceway (MCR) was created to combine the advantages of circular tanks and traditional linear raceways. The conceptual idea was firstly mentioned by Watten *et al.*; the authors converted the raceways into hydraulically separated cells, where each one acts as an individual circular tank. This design provided a good mixing capacity and an absence of dead zones with a low power requirement. A few years later, a large scale MCR prototype was studied by Labatut *et al.* (2007a), water velocities in the tank ranged in the optimum for fish health and provided a good self-cleaning. In another study, Labatut *et al.* (2007b) also simulated a 2D MCR to improve solid wastes removal by using the meshing tool Gamabit 2.1 and the CFD tool Ansys Fluent. The authors found that high rotational velocities were created starting from the tank walls towards the center, which allows the solid effluents to be discharged. The predicted results were correlated with *in situ* measurements (Labatut *et al.*, 2015a).

The novelty of the present study lies in modeling a modified version of the MCR studied by (Labatut *et al.*, 2007b), using the numerical tool Ansys Fluent. The main purpose was to study and evaluate the tank hydrodynamics including water velocity, HRT and power requirements. The results could also confirm the important of CFD method and tools in developing a smart aquaculture.

2. MATERIALS AND METHODS

2.1. Tank design

The studied tank is a combination of the MCR studied by Labatut *et al.* (2007b) and the Burrows tank based on the FAO suggestions for fish farming tanks design. The tank has dimensions of 22 × 5.5 × 1.2 m (l × L × D), contains eight counter-rotating mixed cells, these cells receiving water from two different kinds of vertical pipe sections (single- or double-sided nozzles) with five or ten jet ports of 15 mm diameter (Fig. 1). Inlet water jets were positioned every 5.5 m with a range of nozzles set every 15 cm starting from 5.1 cm from the tank floor.

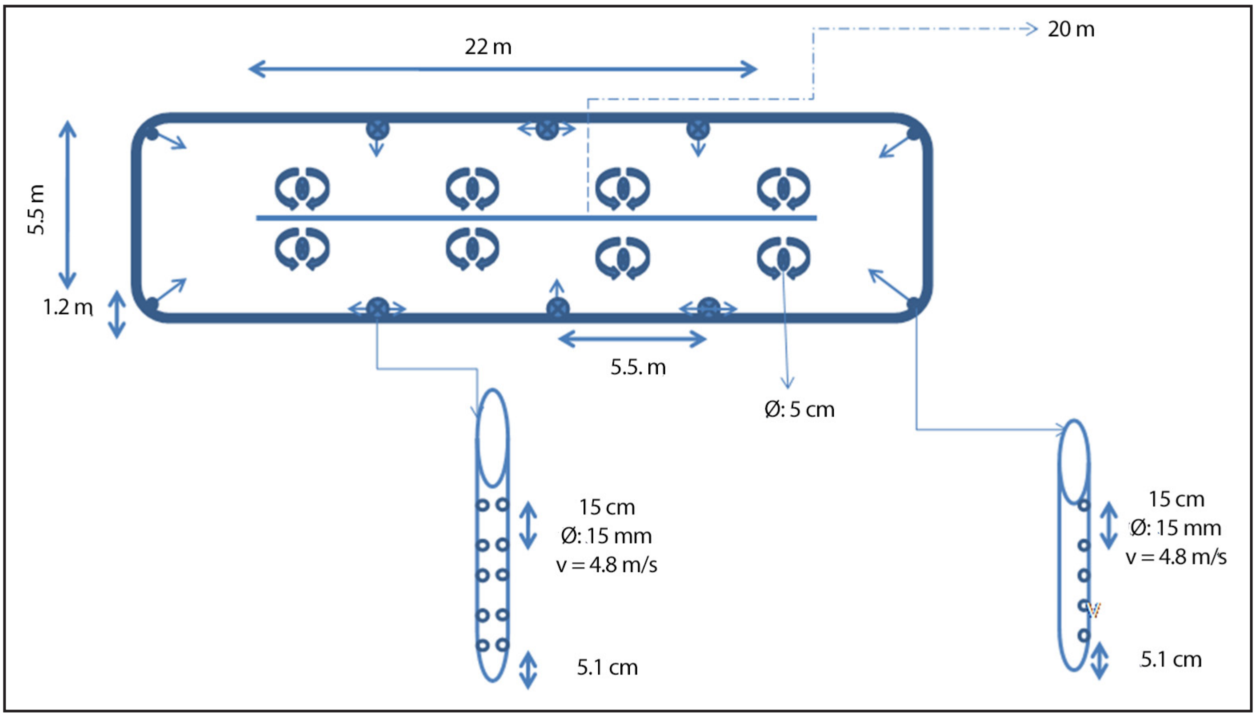

Fig. 1. Plan view of the studied tank.

Unlike the MCR studied by Labatut *et al.* (2007a), this tank doesn't contain any manifolds influent nor does an upper-side drain. Water outlets are centrally located with a 5 cm diameter. As Burrows tank, the studied tank contains a middle wall which is supposed to allow good water mixing. Staggered positioning between water inlets and outlets is recommended by IDEQ (the Idaho Department of Environmental Quality) to avoid dead volumes (IDEQ, 1998).

Hydraulic parameters and characteristics (Table 1) were chosen from previous studies of Labatut *et al.* (2015a) and according to the Brater and King equation (Brater, 1976).

Brater and King equation (1976)

$$U=\frac{Q}{A}=C_d\sqrt{2gh} \qquad (1)$$

With:
U: inlet velocity (m/s);
Q: Inlet flow rate (m^3/s);
A: nozzle cross-sectional area (m^2);
C_d: nozzle discharge coefficient: 0.93;
g: acceleration due to gravity 9.81 m/s^2;
h: hydraulic head (m).

Table 1. Dimensions and operating conditions.

Characteristic	Value
Height (m)	22
Width (m)	5.5
Depth (m)	1.2
Water depth (m)	1.15
Volume (m^3)	145.2
Flow rate (m^3/h)	188.5
Inlet velocity (m/s)	4.6
Renewing rate (v/h)	1.4
Inlet nozzles	61
Inlet nozzle diameter (mm)	15
Inlet flow rate (m^3/h)	2.9
Outlet nozzles	8
Outlet nozzle diameter (cm)	5

2.2. GEOMETRY AND MESH CONFIGURATION

In this study, we used the CFD software Ansys Fluent 16.0, which solves the Reynolds-Averaged Navier–Stokes (RANS) equations of continuity and momentum to simulate water velocity. The flow in the tank was modeled as turbulent. The geometry was created using DesignModeler (Fig. 2), the tank did not contain fish because they are difficult to simulate.

After creating the geometry, the generated mesh was divided into a network of intersecting lines that form nodes, which are the points where the velocity values are calculated. The computational mesh was generated using the Meshing module resulting in 6640125 elements and 1903681 nodes. This mesh was composed of tetrahedral elements and refined near the walls and water inlets/outlets (Fig. 3); this operation creates a maximum of nodes and therefore allows a good accuracy and computational efficiency.

2.3. BOUNDARY CONDITIONS

Boundary conditions used in this study are shown in Table 2. The studied enclosure is assumed to be a fiberglass tank filled with sea water.

Table 2. Boundary conditions.

Parameter	Sea water	Fiberglass
Temperature °C	19.11 (292.26 K)	/
Water density kg/m^3	1025	150
Heat capacity J K^{-1} kg^{-1}	3850	700
Thermal conductivity W m^{-1} K^{-1}	0.5966	0.04
Viscosity kg m^{-1} s^{-1}	$1.070\ 10^{-3}$	/

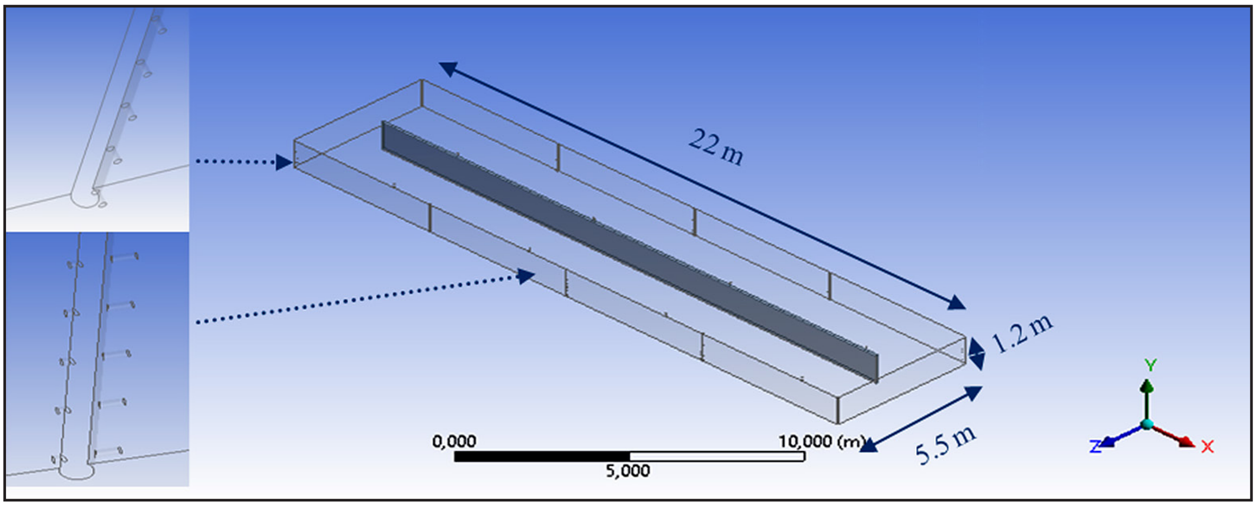

Fig. 2. Geometry of the studied tank.

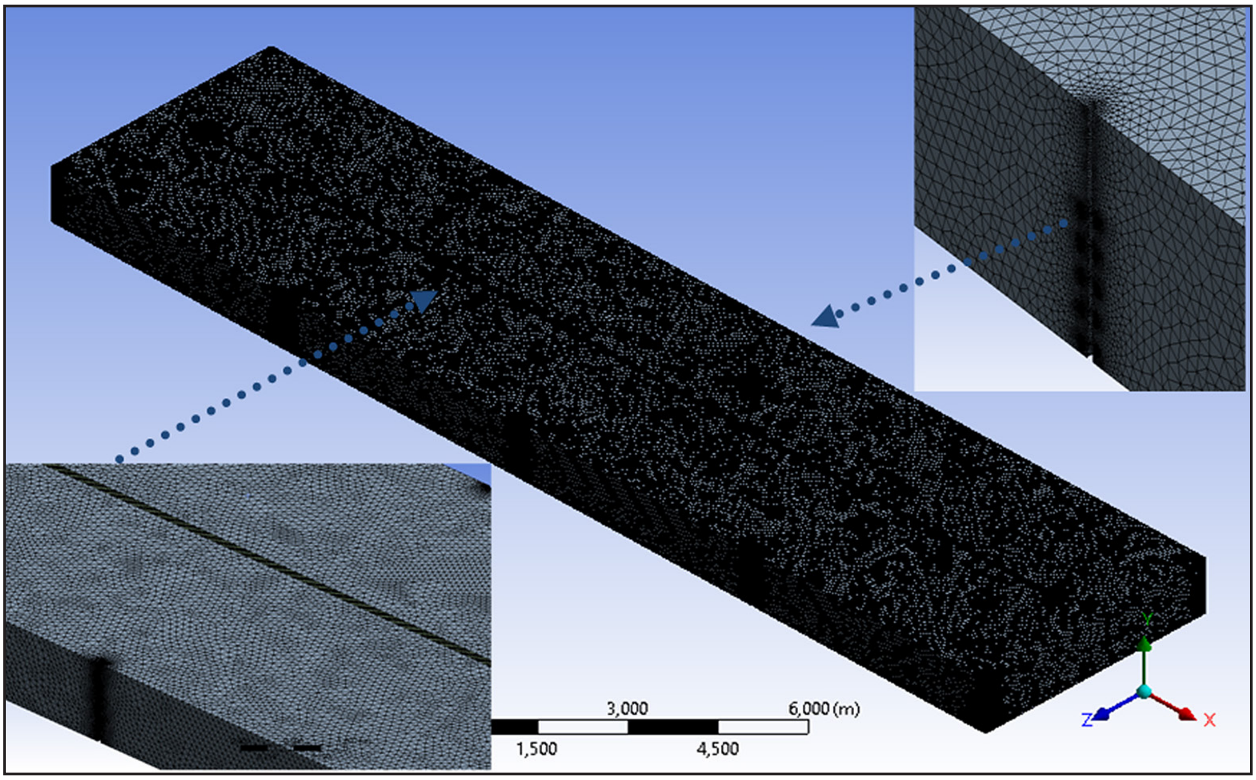

Fig. 3. The studied tank mesh.

2.4. Simulation parameters

Simulations were performed based on hydrodynamic and CFD parameters from previous studies (Labatut *et al.*, 2007a; Zhang *et al.*, 2020) (Table 3). The flow type was defined by the Reynolds number.

Reynolds equation

$$Re=\frac{V\times D}{\nu}=\frac{\rho\times V\times D}{\mu} \qquad (2)$$

With:
V: Flow velocity (m/s);
D: diameter (m);
ν: Kinematic viscosity (m^2/s);
ρ: Density of the fluid (kg/m^3);
µ: Dynamic viscosity (kg/m·s).

The K-ε model has been widely used in aquaculture studies; this model is more suitable for jet and mix flow (Liu *et al.*, 2017). The jet velocity at the water inlet was set at 4.6 m/s.

Table 3. Simulation parameters.

Parameter	Choice
Type of solver	Density based
Velocity formulation	Absolute
Time	Transient
Flow	Turbulent
Gravity	-9.81 m/s^2
Model	Multi-phase off K-ε realizable Standard wall functions
Energy	Energy equation
Radiation	Off
Heat transfer	Off
Species	Off
Solidification and melting	Off
Acoustics	Off
Eulerien film	Off
Materials	Solid/fluid: fiberglass/ Sea water/air
Boundary conditions: Inlet Outlet Wall solid	 Hydraulic diameter, inlet velocity Outlet water

The HRT (Hydraulic Retention Time) was calculated using the following equation:

HRT equation

$$\frac{V}{Q} \qquad (3)$$

With:
V: Total volume (m^3);
Q: Flow rate (l/min).

The power required per volume was calculated according to the Watten *et al.* (2000) equation.

Power requirements equation

$$P=\frac{h\times \rho\times g\times Q}{\eta\times V} \tag{4}$$

With:
P: Power required per volume (W/m^3);
h: hydraulic head (m);
ρ: water density (kg/m^3);
g: acceleration due to gravity (9.81 m/s^2);
Q: Flow rate (m^3/s);
η: pump and mechanical efficiency combined (0.7) according to (Watten *et al.*, 2000);
V: Water volume (m^3).

2.5. Numerical model

Governing equations

The following conditions were assumed in this study: first, the working fluid was considered as incompressible; second, it is assumed that the culture tank system is maintained at a constant temperature (without considering the effect of temperature). Based on the assumption of viscous incompressible fluids, the continuity equation and the Navier-Stokes (N–S) equations are:

- Conservation of mass equation:
- Momentum equation:
- Energy equation:

CFD tools are based on solving fluid flow conservation equations, Ansys Fluent essentially solved the momentum, mass and energy equations:

Conservation of mass equation

$$\frac{\partial \rho}{\partial t}+\nabla.(\rho\vec{v})=S_m \tag{5}$$

Where:
S$_m$: the source;
v: velocity (m/s);
ρ: density (kg/m^3);
t: time (s).

Momentum equation

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla.(\rho\vec{v})\otimes\vec{v}=\nabla.\,\tau^{=}+\vec{F} \tag{6}$$

Where:
$\vec{F}$:the gravitational body force and external body forces (m/s^2);
$\tau^{=}$: the stress tensor (pa);
v: velocity (m/s);
ρ: density (kg/m^3);
t: time (s).

Energy equation (1)

$$\frac{\partial}{\partial t}(\rho e)+\nabla.\left[\vec{v}\,(\rho e+P)\right]= = \nabla.\left[k\nabla T-\sum_j h_j\vec{J}_j+\left(\tau^{=}.\,\vec{v}\right)+s_h\right] \tag{7}$$

Where:
e: total energy (j);
$\vec{J}_j$: diffusion flux of species (W/m^2);
h$_j$: heat source (j);
T: temperature (K);
P: static pressure (pa);
k: thermal conductivity (W/m·K).

Energy equation (2)

$$e=h-\frac{P}{\rho}+\frac{V^2}{2} \tag{8}$$

Where:
h: enthalpy (j/kg).

3. RESULTS AND DISCUSSION

Simulated velocities at the outlet ranged between 0.01 and 0.07 m/s. They are in the optimum range for fish farming and allow a good tank self-cleaning. These results are in agreement with those found by Labatut *et al.* (2015b). Velocities increase progressively toward the center of the center of the outlet orifice, forming a peaked velocity profile. This acceleration is caused by the fluid viscosity, which causes shear stresses between adjacent fluid layers. Conversely, frictional forces at the tank walls reduce water velocities in the near-wall region (Fig. 4).

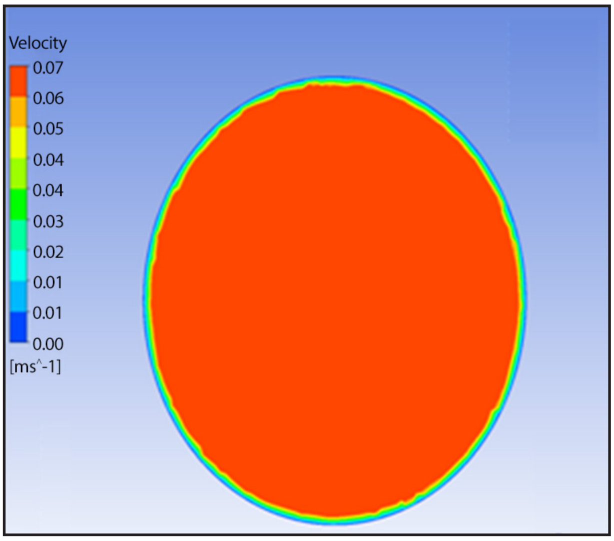

Fig. 4. Velocity contours at the outlet.

Since removing fecal wastes and uneaten feed is a crucial parameter in farming tanks design, the water vortex created in every cell of the tank provides an optimum cleansing of the enclosure. Indeed, this design offers a good biosolids removal since the outlets water configuration allows a rapid evacuation and avoid solids settling and accumulation (Labatut *et al.*, 2007b).

Figure 5 shows the water velocity distribution in the studied tank; predicted water velocities ranged from 3 to 40 cm/s and are located in the recommended velocities for fish farming using MCR tanks studied by Summerfelt *et al.* (2016). Furthermore, Labatut *et al.* (2007a) studied a MCR tank with similar hydraulic parameters; they found an average water velocity of 16.5 m/s. In another study using the same tank Labatut *et al.* (2007b) generated an iso-curve for predicting water velocity in a farming tank using the nozzle diameter and the inlet water velocity. According to this curve and using our parameters; the water velocities in the simulated tank should range from 20 to 30 m/s, indeed the predicted velocities ranged from 3 to 40 cm/s.

The inlets are positioned asymmetrically within the tank, this specific design generating a non-uniform flow creating recirculation zones and vortices as confirmed by Gorle *et al.* (2019). Hence, decreasing velocity magnitude is identified from the inlets due to predominant tangential flow injected from inlet pipes near the walls (Gorle *et al.*, 2018) which create a more uniform waters in the middle of the tank. In a comparative study between a MCR and a Burrows tank, Stockton *et al.* (2016) found higher water velocities in the MCR tank (23 cm/s for 17 cm/s) which allows a good effluents discharge.

Simulating velocity vectors as a function of time is essential for visualizing flow structures (recirculation/ dead zones). Figure 6 illustrates time evolving velocity vectors; a rotational flow is created by inlet waters throughout the tank and a mixing layer is established as time goes by. This mixing parameter depends on the inlet and outlets configuration (number, position and orientation) and also the hydraulic conditions such as the velocity and diameter (Oca & Masalo, 2013). A velocity linear gradient is also observed from the walls to the tank entrances, as confirmed by Papáček *et al.* (2020) and Stockton *et al.* (2016).

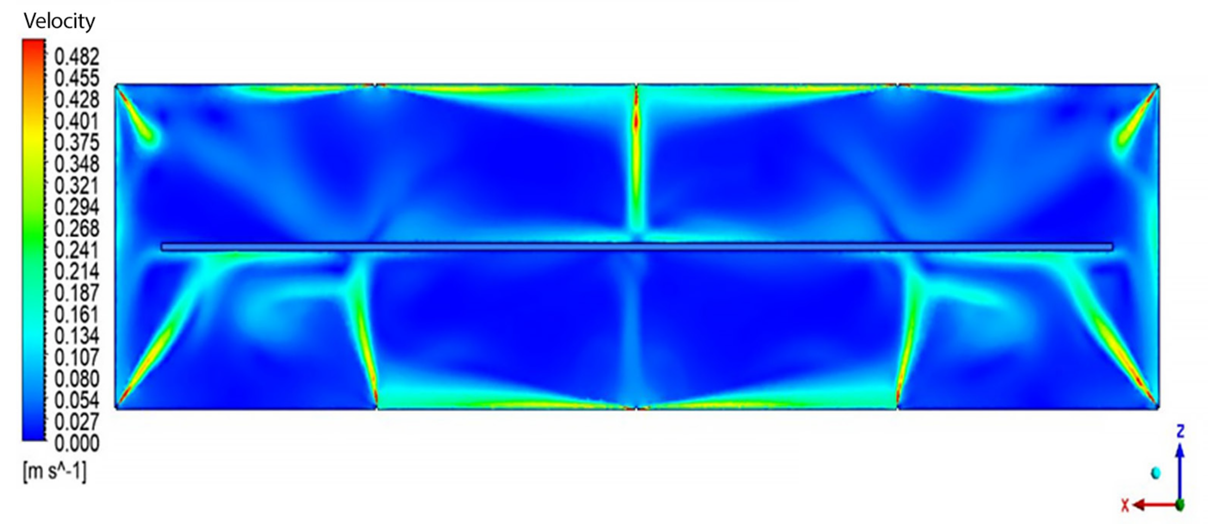

Fig. 5. Water velocity distribution in the studied tank.

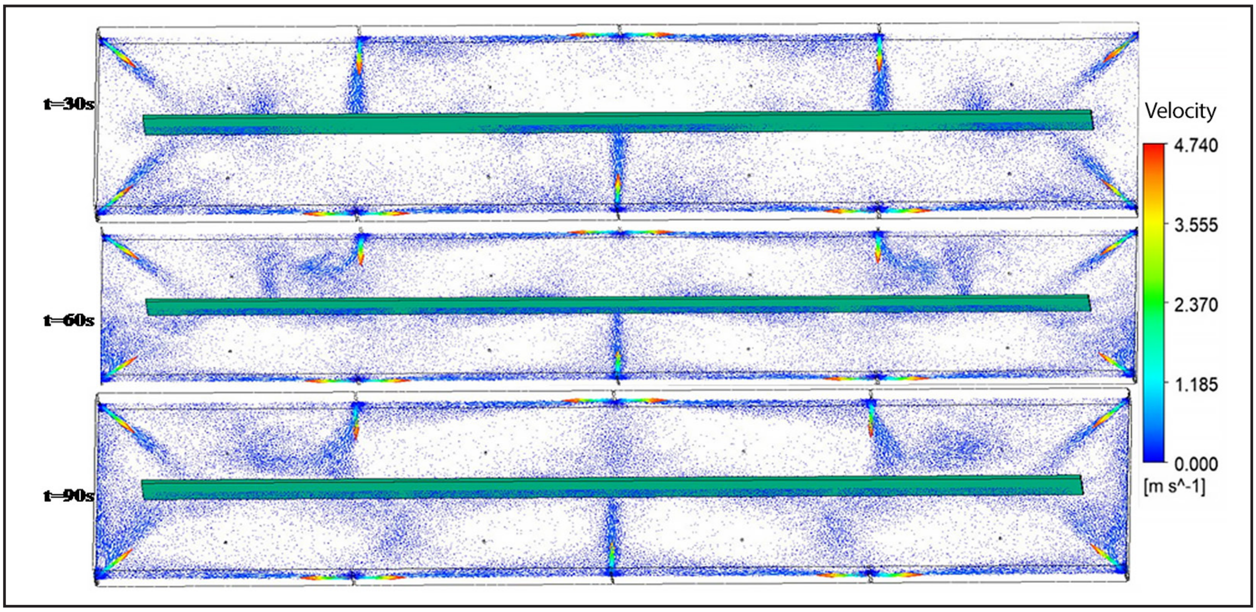

Fig. 6. Velocity vectors in the studying tank according to time.

Studying water vorticity in a fish farming tank provides meaningful information on waste removal and energy costs. Vorticity distribution at the bottom, the middle and the top of the tank are shown in figure 7. Vorticity patterns showed a good mixing capacity and an absence of dead zones in the top water layers. Water velocities increased toward the bottom since the inlets water were located 54.9 cm below the water surface. Indeed, Choi *et al.*, (2023) confirmed that modifying the nozzle angle and increasing the number of inlets can remove dead zones. Hence changing the geometries and designs of farming tanks can improve hydrodynamic performance and facilitate fish growth (Choi *et al.*, 2023).

The HRT (Hydraulic Retention Time) in the studied tank is 46 minutes; similar to Watten *et al.* (2000) results. This value is also in the range observed by Summerfelt *et al.* (2016) for commercial MCR (34.8 min - 52.5 min). Indeed, the authors confirm that the HRT tend to be reduced in modern fish farms (Summerfelt *et al.*, 2016). The HRT found allows good water mixing; it is actually one of the important parameters in fish tanks design since it is used to evaluate water mixing uniformity and dead zones creation, which offer an optimum water quality and feed distribution throughout the tank (Labatut *et al.*, 2007b).

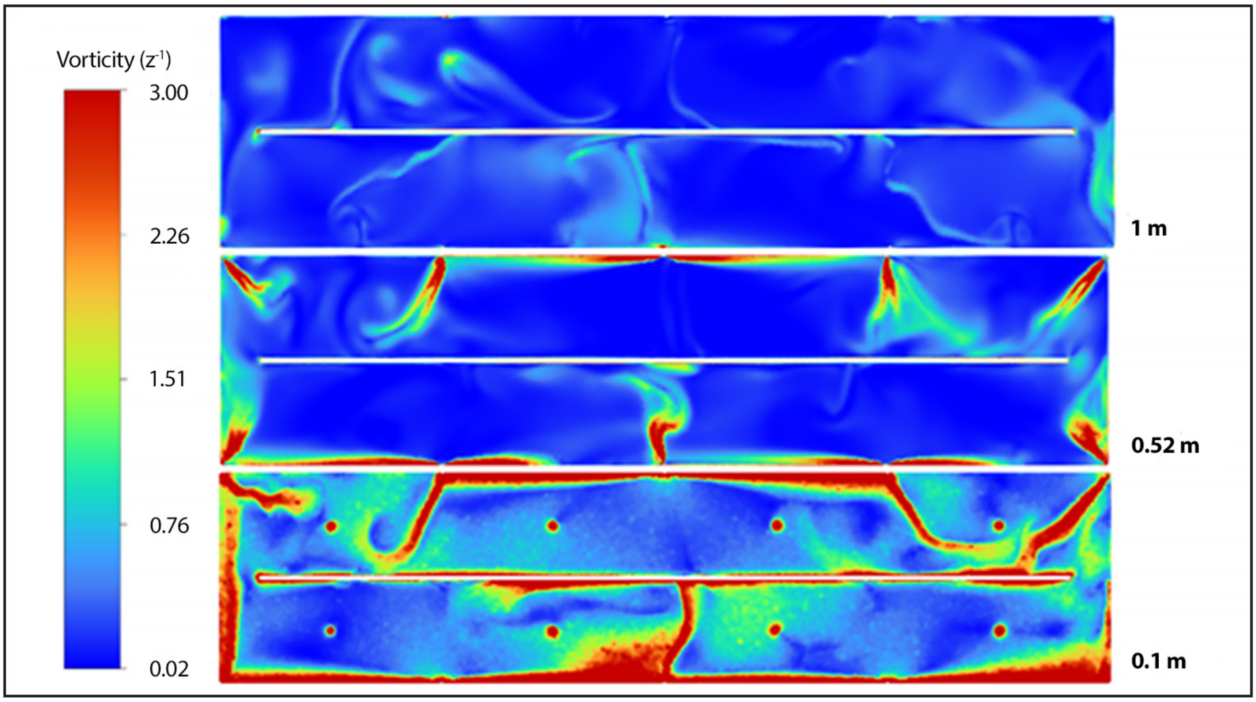

Fig. 7. Vorticity distribution in the studied tank.

The calculated power requirement was 6.03 W/m^3. Using the same nozzle diameter and with a tank volume of 104.4 m^3, Labatut *et al.* (2007b) found 6.6 W/m^3.This result confirms that adding a cell in the tank offers a higher fish stoking density without needing a bigger power. As a matter of fact, the power requirement depends on the inlet nozzle diameter and the water exchange rate. Furthermore, Fox & Gex (1956) argue that increasing inlets water reduce the power consumption in the tank.

Space occupation, fish well-being and the power requirement are the main parameters in validating a tank design. These shapes are gathered in the studied tank, hence the tank geometry is adequate and allows a good carrying capacity with appropriate velocities and an absence of dead zones. Furthermore, this tank showed a fairly power requirement.

4. CONCLUSION

Overall predicted water velocities in the studied tank were located in the optimum range for fish farming. A decreasing water velocity was observed from the periphery to the center and from the tank floor to the water surface. Water velocities in farming tanks depend on the inlet-outlet configuration (number, diameter and orientation) and the inlet water velocity (jet velocity). The studied tank rounds up the advantages of a MCR and a Burrows tank and provide an optimum hydrodynamic parameters and conditions for fish husbandry. This study can be used as a basis for a prototype and an experimental test with considering fish motions and there effects on water velocities distribution and effluents discharge,

Modern aquaculture must consider sustainable development and thus by using modeling and CFD tools to optimize different rearing tanks and farming systems. CFD tools could be used to optimize and improve existing tank design, or to model new enclosures before the manufacturing process. Indeed, CFD modeling may help in reducing test costs and experiments time.

AUTHORS' CONTRIBUTIONS

Conceptualization: YIA, MATM, Data Curation: YIA, Formal Analysis: MATM, Methodology: YIA, Writing – Original Draft Preparation: YIA, Writing – Review & Editing: YIA, MATM.

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CONFLICTS OF INTERESTS

The authors assert that they have no conflict of interest.

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