A method for minimizing the zone of low water flow velocity in a bottom center drain circular aquaculture tank

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Abstract

Bottom center drain circular tanks in which water is injected tangentially to the tank wall are widely used in aquaculture. However, a torus-shaped region about the center drain can develop into an irrotational zone that generates low velocities and poor mixing. Many works have been devoted to improving tank hydraulics by making good use of the water flow pattern. However, mathematics-friendly methods, such as the statistical optimization method, which is widely used in science and engineering, are rarely used in aquaculture tank designing. This work focuses on the minimization of the low velocity zone in a bottom center drain tank based on experimental planning and computational fluid dynamics. Model validation was carried out by comparison with measurements. The results show that the low velocity zone can be reduced measurably by the proposed method.

KEYWORDS

circular culture tank, computational fluid dynamics simulations, experimental planning, hydraulics, low velocity zone

1 | INTRODUCTION

Circular center drain tanks with tangential inlet are widely used in aquaculture. However, the no-slip condition that exists between the primary rotational flow and the tank's bottom and sidewalls creates a secondary flow. With this
Aquaculture tank hydraulics are mainly dependent on the tank geometry and the properties of water inlet and outlet (Masaló, 2008; Oca & Masaló, 2013). Larmoyeux, Piper, and Chenoweth (1973) suggested that the ratio of diameter to depth ranging from 5:1 to 10:1 would prevent the appearance of irrotational zone. Some researches on water nozzle designs in circular tanks (Labatut, Ebeling, Bhaskaran, & Timmons, 2007; Tvinnereim & Skybakmoen, 1989; Watten, Honeyfield, & Schwartz, 2000) showed that configurations with a vertical pipe containing evenly distributed nozzles produce more homogeneous flow distribution, compared to the inlet designs with a single point source.

Oca and Masaló (2013) analyzed the influence of tank characteristics (diameter, water height, and roughness) and water inlet and outlet features (flow rates, impulse forces) on the distribution of water velocities in aquaculture tanks. Rotational velocity about the perimeter of circular tanks is strongly dependent on the impulse force of water flow injected tangentially into the circular tank (Davidson & Summerfelt, 2004; Oca & Masaló, 2013; Plew, Klebert, Rosten, Aspaas, & Birkevold, 2015; Prabhu et al., 2017; Tvinnereim & Skybakmoen, 1989; Venegas, Narvaez, Arriagada, & Llanc aleo, 2014).

Recent works on the hydraulics in fish culture tanks show a tendency to focus more efforts than ever before on nozzle parameters such as inlet and/or outlet placement, nozzle arrangement and injection flux as well as tank geometry (An et al., 2018; Gorle, Terjesen, & Summerfelt, 2018, 2020). Davidson and Summerfelt (2004) showed how Cornell-type dual-drain system affects solid flushing, water mixing, and water velocity profiles in circular tanks, while Gorle et al. (2018) showed how that affects hydrodynamics in octagonal tanks. An et al. (2018) showed the effect of bottom center/eccentric drains on hydraulics in large circular tanks by using computational fluid dynamics (CFD) simulations. Gorle et al. (2020) showed that the inlet and outlet positions considerably influence the flow pattern and solid removal. They demonstrated that the water flow uniformity and circulation characteristics in a large octagonal tank were much improved when using the bottom-drain and corner-inlet options than when using the elevated drain at the tank’s center and sidewall-inlet options.

One of the most fundamental objectives of all hydraulics research in the fish culture tanks is to minimize the volume of low velocity zone (VLVZ) in order to optimize the utilization of the water and the available space in the tanks. The aim of the present work is to determine the optimal design parameters for minimizing VLVZ by using the experimental planning and CFD simulations in a bottom center drain circular tank.

2 | MATERIALS AND METHODS

This work focuses on the water flow in circular tanks with no fish. It can be a prerequisite for studying the influence of fish swimming and turbulence on the flow pattern in the tanks (Masaló & Oca, 2016; Plew et al., 2015). CFD code FLUENT 6.3 was used for numerical experiments.

2.1 | Experimental planning

Experimental planning (Jeffwu & Hamada, 2001) is a branch of quality management. This is a statistical-mathematical method that enhances the quality of products at the lowest cost in production. It sets the factors that affect the qualities of products and reveals the optimal conditions to get the highest quality with the fewest experiments. This method consists of selecting the factors, leveling factors, computing signal-to-noise ratios, and getting the optimal conditions. We have shifted the problem from quality enhancement to minimization of VLVZ to apply the experimental planning.
2.2 Governing equations

The governing equations for incompressible viscous fluid, commonly used here, are as follows:

- continuity equation;
- momentum equation; and
- turbulence, shear stress transport (SST) $k-\omega$ model.

For turbulence in the fish culture tanks, the SST $k-\omega$ model was selected unlike some previous works (Huggins, Piedrahita, & Rumsey, 2005; Peterson, Harris, & Wadhwa, 2000), in which they made little use of the $k-\varepsilon$ model. The $k-\varepsilon$ model is a high Reynolds number turbulence model, valid only for fully turbulent shear flows that cannot be integrated all the way to the wall, while the SST $k-\omega$ model can simulate a low Reynolds number turbulence in the boundary layer near the wall (Moukalled et al., 2016). The turbulence model was chosen based on our view that the effect of drain position on tank hydraulics might depend on the interaction between wall structure and water flow.

2.3 Geometry and grid models

Geometry model of the tank and the water inlet are shown in Figure 1. The water inlet is a single vertical pipe with six nozzles. Every nozzle has an identical injection speed of 0.67 m/s which is explained below.

Before particular meshing, the whole domain including the vicinity of the nozzle pipe was divided into subdomains, each of which is topologically equivalent to hexahedron. When dividing the whole domain with those subdomains, it is easy to fill every subdomain with single-typed hexahedral cells, which enables to get a grid model consisted of structured mesh. Among the grid models with mesh-independence for each tank, one with the smallest number of cells was chosen for simulation. Those grid models had about 2,267,400 cells for the 7-m-diameter tank. More details for the grid model are in An et al. (2018).

2.4 Boundary conditions

Water at initial rest is accelerated by injection from all the nozzles until the rotating flow reaches the steady-state in which flow variables do not change with time. The primary water injection speed at nozzles was determined by the equation from Paul, Sayal, Sakhuja, and Dhillon (1991), which reflects an approximate relationship between the rotational velocity in the tank, $v_{rot}$ and the velocity at the water inlet near the tank wall, $v_{orif}$, that is,
\[ v_{rot} \approx \alpha V_{orif}, \]

where \( \alpha \) is a proportionality constant taken from 0.15 to 0.20 (Timmons et al., 1998). When \( v_{rot} \) and \( \alpha \) were set at 0.1 and 0.15 m/s, respectively, the nozzle injection speed was determined to be 0.67 m/s.

These values were chosen as velocity inlet conditions at the nozzle orifices. A symmetry condition was applied to the water surface, while no-slip condition was applied to the solid boundaries of tanks. The pressure outlet boundary of zero gauge pressure was specified to the outlet of the drain pipe. Every steady rotating flow field was obtained when the plot that shows size-average of velocity size on the water surface develops into an unchangeable horizontal line.

3 | RESULTS AND DISCUSSION

3.1 | Optimization criterion

The average velocity (AV) of the water flow in a fish culture tank is a key parameter related to the hydraulic of tank. However, the AV alone is not enough for representing water flow patterns of a culture tank, particularly, the characteristics of the irrotational low velocity zone around the center drain. So, we selected the VLVZ as an optimization criterion and coded a user defined function which computes the sum of cell volumes with velocity less than a limit velocity. The limit selected based on our experience in this work was \( 10^{-6} \) m/s. Figure 2 shows an example of flow pattern in the water tank under consideration.

At the beginning of the optimization, the effect of nozzle pipe distance from the center drain on VLVZ and AV was investigated numerically (see Table 1).

The correlation coefficient of the VLVZ and AV is \( R_{VA} = -0.45 \) (Table 1). Figure 3 shows the profiles of the water velocity magnitude on a vertical plane across the tank center at different nozzle pipe distances from the tank center.

Table 1 shows that the VLVZ is proportional to the distance between the nozzle pipe and tank center, while AV inversely proportional. Figure 3 shows that the velocity magnitude is not proportional to the tank radius as much as above distance decreases, which is very clear in Figure 3(e). The results in Table 1 and Figure 3 show that the nozzle properties including the distance can have a significant influence on the water flow behavior in the circular tank.

**FIGURE 2** Velocity magnitude patterns in the tank shown in Figure 1. (a) Pathlines show the rotating flow pattern and (b) contour on the water level shows the configuration of low velocity zone.
means that, when we set the distance between the center drain and the nozzle pipe as a factor, we have to regard the configuration of the water flow velocity distribution like in Figure 3.

| Distance (m) | VLVZ (m³) | AV (m/s) |
|-------------|-----------|---------|
| 3.1         | 14.5      | 0.098   |
| 3.0         | 11.5      | 0.101   |
| 2.9         | 9         | 0.104   |
| 2.8         | 8.05      | 0.108   |
| 2.6         | 5.8       | 0.113   |

Abbreviations: AV, average velocity; VLVZ, volume of low velocity zone.

**FIGURE 3** Velocity magnitude distributions on a vertical plane at nozzle pipe distance of (a) 3.1 m, (b) 3.0 m, (c) 2.9 m, (d) 2.8 m, and (e) 2.6 m. (f) Selected plane

3.2 | Optimization of the VLVZ

As mentioned above, the aim of this work is to find the circular tank geometry with minimum VLVZ. We intend to solve the problem of optimization by applying the method of experimental planning (Jeffwu & Hamada, 2001). Our optimization study is divided into two steps. In Step 1, we evaluate the general effects of the tank geometry and the
injection conditions by setting the tank diameter, water depth, depth of the bottom, the position of the nozzle pipe, and the position of the first nozzle as 2-level factors and calculating their contribution rates to get a tendency. In Step 2, considering their contribution rates and the practical situation, we choose fewer factors and arrange them in a three-level orthogonal table to obtain the optimal conditions. In Steps 1 and 2, we disregard the interaction effects of the factors.

### 3.2.1 Objective and factors
Optimization objective and factors in step 1 were selected as in Table 2.

### 3.2.2 Factor levels
Factor levels in Step 1 set to considering their effects on the results of experiments (see Table 3).

### 3.2.3 Orthogonal table and signal-to-noise ratio
Arrangement in an orthogonal table $L_8(2^7)$ and numerical experiments were performed. Table 4 shows signal-to-noise ratio calculated from measurements of the VLVZ at each experimental point.

Because HRTs are the ratios between the water volume or VLVZ in tank and the same feed flux, VLVZ/Vts are the same with HRTv/HRTts as shown in Table 4. Tables 5 and 6 are the subtable and variance analysis table from the above data, respectively.
Because the variance of the factor B is smaller than that of the error variation, it is involved in the integrated error variation. Table 7 shows optimal conditions of Step 1 obtained from the above subtable when there is no tangle of factors.

We set the tank diameter with contribution rate of 35% at 7 m, whereas water depth with comparatively low contribution rate was fixed at 1.2 m considering the fact that the diameter is proportional to the depth.

**TABLE 4** Orthogonal table $L_8(2^7)$ and signal-to-noise ratio in Step 1

| No | A | B | C | D | E | F | G | V_t (m$^3$) | HRT_t (min) | VLVZ (m$^3$) | VLVZ/V_t (HRT_v/HRT_t) | S/N |
|----|---|---|---|---|---|---|---|-------------|-------------|-------------|----------------------|-----|
| 1  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 57.7        | 187.2       | 16.9        | 0.29                 | 11.9 |
| 2  | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 55.7        | 180.8       | 9.6         | 0.17                 | 34.6 |
| 3  | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 65.3        | 211.9       | 21          | 0.32                 | 9.8  |
| 4  | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 63.4        | 205.7       | 14.7        | 0.23                 | 18.9 |
| 5  | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 75.3        | 244.4       | 25          | 0.33                 | 9.18 |
| 6  | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 72.7        | 235.9       | 34.6        | 0.47                 | 4.5  |
| 7  | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 85.3        | 276.8       | 28.6        | 0.33                 | 9.18 |
| 8  | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 82.7        | 268.4       | 32          | 0.38                 | 6.9  |

Notes: HRT_t and HRT_v is HRT of V_t and VLVZ, respectively. VLVZ/V_t (HRT_v/HRT_t) means that VLVZ (HRT_v) is divided by V_t (HRT_t). S/N values means 1/ (VLVZ/V_t)$^2$ values.

Abbreviations: HRT, hydraulic retention time; S/N, signal-to-noise ratio; VLVZ, volume of low velocity zone; V_t, water volume in tank.

**TABLE 5** Subtable

| Factors | Level 0 | Level 1 |
|---------|---------|---------|
| A       | 75.2    | 29.76   |
| B       | 60.18   | 44.18   |
| C       | 62.58   | 42.38   |
| D       | 40.06   | 64.9    |
| E       | 33.1    | 71.86   |
| F       | 46.88   | 56.08   |

**TABLE 6** Variance analysis table

| Factors | Variation | Degree of freedom | Net variation | Contribution rate (%) |
|---------|-----------|-------------------|---------------|-----------------------|
| A       | 258.9     | 1                 | 234.1         | 35                    |
| B       | 17.17     | 1                 |               |                       |
| C       | 51.88     | 1                 | 27.08         | 4                     |
| D       | 78        | 1                 | 53.2          | 8                     |
| E       | 188.6     | 1                 | 163.4         | 25                    |
| F       | 98.2      | 1                 | 73.4          | 11                    |
| e (error) | 56.8     | 1                 |               |                       |
| Integrated variation | 651.35    | 7                 |               |                       |

Because the variance of the factor B is smaller than that of the error variation, it is involved in the integrated error variation. Table 7 shows optimal conditions of Step 1 obtained from the above subtable when there is no tangle of factors.

We set the tank diameter with contribution rate of 35% at 7 m, whereas water depth with comparatively low contribution rate was fixed at 1.2 m considering the fact that the diameter is proportional to the depth.
In Step 2, the objective for optimization also concerns the VLVZ. The position of the nozzle pipe, the space between nozzles, the drain depth, and the first nozzle position were chosen as factors (Table 8). The levels of position of the nozzle pipe were set with regard to the velocity magnitude profiles in Figure 3(e). Table 9 shows the factor levels. Table 10 shows signal-to-noise ratio calculated from measurements of the VLVZ at each experimental point of an
orthogonal table L9(3^4). Tables 11 and 12 are the subtable and variance analysis table from the above data, respectively.

As shown in Table 12, we can see that the contribution rate of the nozzle pipe position is considerably higher, compared with the other factors. In other words, the right positioning of the nozzle pipe is of great significance in reducing VLVZ. The optimal conditions obtained through two steps are shown in Table 13.

Comparison between the VLVZ simulated in the optimized tank and the one in the prototypical tank (An et al., 2018), whose diameter, water depth, drain depth, nozzle pipe position, space between nozzles, and first nozzle position were 7, 1.2, 0, 3.1, 0.17, and 0.07 m, respectively, are given in Table 14.

As shown in Table 14, under the optimal conditions, the VLVZ per unit volume can be reduced as small as about 1/2 of the prototypical. Velocity magnitude distributions of the prototypical tank and optimized tank can be obtained in Figure 3(a) and (b), respectively. From Figure 3(a) and (b), we can see that an optimized tank has better uniformity of velocity magnitude, compared with the prototypical tank. Figure 4 shows the flow pattern in the water tank under the optimal condition.

Figure 5 shows the position (point C) of the nozzle pipe under the optimal conditions. In the figure, $|AC|$ refers to the distance from the tank wall to the vertical nozzle pipe, that is,

$$|AC| = 0.7 \text{m}, \frac{AC}{CB} = 0.7/1.05 = 0.66.$$

An imposing result is that the point C divides the segment AB or the semi-radius in a golden ratio.

| TABLE 11 | Subtable |
|-----------|----------|
| **Factor** | A | B | C | D |
| Level 0 | 115 | 118 | 94.1 | 150.9 |
| Level 1 | 186.8 | 173.3 | 122 | 94.7 |
| Level 2 | 50.5 | 64.6 | 141 | 106.7 |

| TABLE 12 | Variance analysis table |
|-----------|-------------------------|
| **Factor** | **Variation** | **Degree of freedom** | **Variance** | **Net variation** | **Contribution rate (%)** |
| A | 3,053.3 | 2 | 1,526.65 | 2,926.4 | 70 |
| B | 698.2 | 2 | 349.1 | 571.3 | 13 |
| C (e) | 126.9 | 2 | 63.45 |  |
| D | 303.7 | 2 | 151.85 | 240.25 | 6 |
| Integrated variation | 4,182.1 | 8 | |

| TABLE 13 | Optimal conditions |
|-----------|-------------------|
| Tank diameter | 7 m |
| Water depth | 1.2 m |
| Nozzle pipe position | 2.8 m |
| Space between nozzles | 0.17 m |
| Drain depth | 0.1 m |
| First nozzle position | 0.02 m |
3.4 Validation

The measuring of water flow velocity was carried out in a modified 7-m-diameter tank. In the tank, the nozzle pipe was modified and moved according to Table 13. Injection speed of 1.34 m/s which was the highest one in An et al. (2018) was applied because the lower injection speed including 0.67 m/s was considered to be excluded from the viewpoint of measurement accuracy. The other experimentation was the same as in An et al. (2018). It deserves special emphasis that the horizontal velocity was measured at positions \(A_i\) \((i = 1, 2, 3)\) and \(B_i\) \((i = 1, 2, 3)\), while the vertical velocity at positions \(C_i\) \((i = 1, 2, 3)\) (see fig. 3 in An et al., 2018). Tables 15 and 16 show measured and simulated values of the horizontal and vertical velocities.

As shown in Table 17, under the optimal conditions, the VLVZ per unit volume was reduced as small as about 1/2 of the prototypical, while the measured and simulated AVs was a little increased.

TABLE 14 Comparison of VLVZ per unit volume in two cases

|   | \(V_t\) (m\(^3\)) | VLVZ (m\(^3\)) | VLVZ/\(V_t\) |
|---|-------------------|----------------|--------------|
| PT | 46.08             | 11             | 0.238        |
| OT | 47.4              | 6              | 0.126        |

FIGURE 4 Velocity magnitude patterns in the optimized tank. (a) Pathlines show the rotating flow pattern and (b) contour on the water level shows the configuration of low velocity zone.

FIGURE 5 Position of the nozzle pipe under the optimal conditions.
Trace particle tracking experiments for observing the effect of nozzle pipe position on the water flow pattern were carried out in a miniature tank with the ratio of 1:10, in which the vertical nozzle pipe is able to move toward the tank center (Figure 6).

**TABLE 15** Measured and simulated values of horizontal velocity

| Measuring point | Measurement (m/s) | Simulation (m/s) |
|-----------------|-------------------|------------------|
| A1              | 0.29              | 0.325            |
| A2              | 0.33              | 0.365            |
| A3              | 0.37              | 0.387            |
| B1              | 0.29              | 0.312            |
| B2              | 0.31              | 0.314            |
| B3              | 0.33              | 0.338            |

**TABLE 16** Measured and simulated values of vertical velocity

| Measuring point | Measurement (m/s) | Simulation (m/s) |
|-----------------|-------------------|------------------|
| C1              | 0.15              | 0.167            |
| C2              | 0.36              | 0.358            |
| C3              | 0.57              | 0.578            |

**TABLE 17** The AVs measured, AVs simulated in two cases

|                 | Measured AV<sub>AB</sub> (m/s) | Simulated AV<sub>AB</sub> (m/s) | Measured AV<sub>C</sub> (m/s) | Simulated AV<sub>C</sub> (m/s) | VLVZ per unit volume |
|-----------------|---------------------------------|---------------------------------|--------------------------------|--------------------------------|----------------------|
| PT              | 0.315                           | 0.335                           | 0.346                         | 0.322                         | 1.21                 |
| OT              | 0.320                           | 0.340                           | 0.360                         | 0.367                         | 0.68                 |

Note: AV<sub>AB</sub> and AV<sub>C</sub> means the average velocities obtained on the measuring point (A<sub>i</sub>, B<sub>i</sub>) and C<sub>i</sub>, i = 1, 2, 3, respectively. Abbreviations: AV, average velocity; OT, optimized tank; PT, prototypical tank; VLVZ, volume of low velocity zone.

**FIGURE 6** Particle tracking experiment. R is tank radius, d is the distance between tank center and nozzle pipe. (a) Experimental setup, (b) d = 5R/6, (c) d = 3R/4, (d) d = R/2, and (e) d = R/3

Trace particle tracking experiments for observing the effect of nozzle pipe position on the water flow pattern were carried out in a miniature tank with the ratio of 1:10, in which the vertical nozzle pipe is able to move toward the tank center (Figure 6).
The observation shows the feature of assembling solids on the tank floor toward the center-drain within the same amount of time, which happens when we place vertical nozzle pipe in various positions.

Figure 6 shows the settling behaviors of solid particles on the tank bottom at different nozzle pipe distances under the same conditions including the injection time and speed. As shown in Figure 6, the shorter the distance is, the more the particles are settled around the drain. It makes us to expect that minimizing the VLVZ could result in improving the self-cleaning capability of tank (Figure 6b,c).

4 | CONCLUSION

In this article, a combined CFD-experimental planning method for minimizing VLVZ in a bottom center drain circular water tank was proposed. The results show that the nozzle pipe position is one of the most important factors in controlling VLVZ. Its optimal position might be related to the golden ratio on the periphery-side semi-radius. The correlation coefficient between AV and VLVZ is negative. Model was validated against measurements. The results show that VLVZ can be reduced when using proposed method. The particle tracking experiments shows a possibility to improve the self-cleaning capability of tank by adjusting the nozzle pipe position.

It should be mentioned that the results and conclusions in the present work might be appropriate to only circular tanks with diameter of about 7 m. Future research will be focused on designing a bottom double drain circular aquaculture tank (combined center-eccentric) in an optimal way and on designing the tanks with the movable nozzle pipe toward center drain.

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AUTHOR CONTRIBUTIONS

Designed the research work: MGS; performed the simulations: CHA, SJC; performed the optimization research: MGS, MJK; performed the experiments: HNK; wrote the paper: MGS.

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