Recirculating Aquaculture System Design and Water Treatment Analysis based on CFD Simulation

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Abstract

As demands for efficient and echo-friendly production of marine products increase, smart aquaculture based on information and communication technology (ICT) has become a promising trend. The smart aquaculture is expected to control fundamental farm environment variables including water temperature and dissolved oxygen (DO) levels with less human intervention. A recirculating aquaculture system (RAS) is required for the smart aquaculture which utilizes a purification tank to reuse water drained from the water tank while blocking the external environment. Elaborate water treatment should be considered to properly operate RAS. However, analyzing the water treatment performance is a challenging issue because fish farm circumstance continuously changes and recursively affects water fluidity. To handle this issue, we introduce computational fluid dynamics (CFD) aided water treatment analysis including water fluidity and the solid particles removal efficiency. We adopt RAS parameters widely used in the real aquaculture field to better reflect the real situation. The simulation results provide several indicators for users to check performance metrics when planning to select appropriate RAS without actually using it which costs a lot to operate.

Keywords: Circular tank, Computational fluid dynamics (CFD), Recirculating aquaculture system, Smart aquaculture, Water treatment

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1. Introduction

There has been increasing interest in maximizing fishing efficiency with limited resources. In addition, eco-friendly system operation has been highly considered to deal with the environmental issues. Accordingly, the aquaculture industry also has been trying to reflect these requirements. In conventional aquaculture systems, administrators play a key role in operation including water management, feeding and production. It means that all components of aquaculture should be manually controlled which could cause unexpected human-error such as water quality degradation and labor shortage. In contrast, smart aquaculture relies on information and communication technology (ICT) to handle those problems in typical fish farms. A conversion to smart aquaculture is expected to enable not only automatic operation but also eco-friendly and efficient production for marine products [1-4]. Studies have been carried out to enhance the aquaculture operation performance [5-7]. In [8], a thermal growth coefficient (TGC) concept was introduced which has been widely used to predict the fish growth rate. TGC takes an accumulated weight and temperature to calculate the weight variation. In [9], a fish activity based adaptive smart feeder minimizing the conventional fisherman’s intervention was proposed. The optimization problem of overstocking determination for aquaculture management was proposed in [10]. The authors in [11] addressed the oxygen, carbon dioxide, and ammonia levels of water for salmon aquaculture. Meanwhile, machine learning (ML) techniques have been applied in the aquaculture field [12-14]. The authors in [15] presented a fish recognition method based on iris images and showed the possibility of a fully automated fish identification system. In [16], a low-cost underwater imaging system using a lightweight deep learning model was proposed to detect fish behavior. However, the existing research has focused on the fish nutrition related to the fish growth and rarely considered the system design. This is because as the system is advanced, the factors to be considered also increase and methodology to analyze the system performance is not determined yet. Nevertheless, the system design and analysis are essential to take advantage of the smart aquaculture.

One of the essential requirements for the smart aquaculture is a recirculating aquaculture system (RAS) design [17]. The RAS rears fish in the indoor tanks under controlled circumstance instead of the traditional fish farm systems such that grow fish outdoors which are exposed to changing environment. RAS blocks the external environments for farming aquatic organisms such as salmon, flatfish, etc., which leads to control of a specific nurturing environment. Therefore, RAS can be used to reserve several particular species. Currently, either circular or octagonal shaped water tank is widely used for RAS [18]. The overall flow of RAS is described in **Fig. 1**. Several additional functions such as temperature control and pH control also can be added. The principal property of RAS technology is recirculating or reusing the water by using a purification tank [19]. Thus, RAS is beneficial for saving water resources, which enables environment-friendly production and contributes to the reduction of farm operation costs. Thanks to these benefits, RAS has been popular in many fields of fishing. However, elaborate water treatment is also required for efficient RAS management [20]. Here, the water treatment covers maintaining the nurturing conditions of the tank like water temperature and dissolved oxygen (DO) levels which are significant for better growth [21]. In addition, the water treatment also needs to consider removing the solid wastes from excretions released by fish and surplus feeds [22]. The critical factors for such water treatment are the flow characteristics of the tank such as water rotation velocity and flow rate change. There is a number of RAS design parameters such as the shape of the water tank, inlet/outlet size, etc. affecting to the flow characteristics which leads to highly increase RAS design complexity.

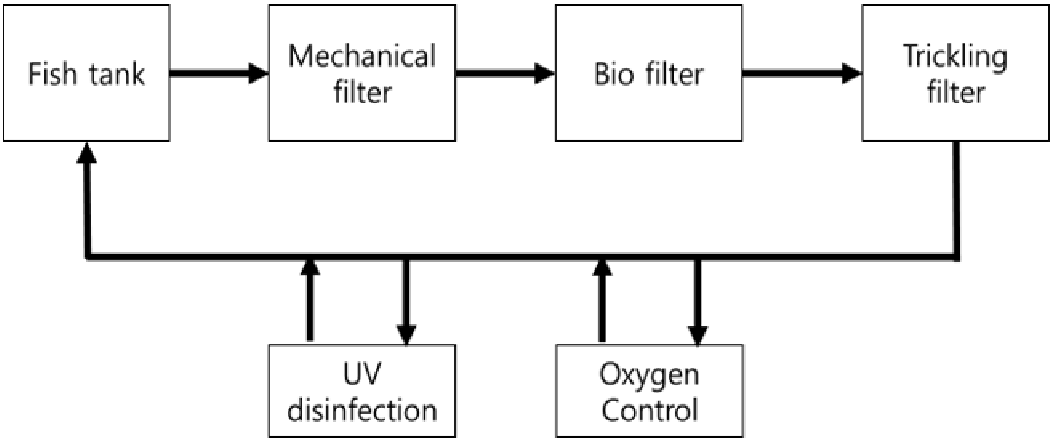

Fig. 1. Overall flow of RAS [19]

In order to control external environment, analyzing the water treatment performance as well as the flow characteristics under the constantly changing internal environment is necessary [23]. Nevertheless, considering the time and cost for farm operation, the RAS design while changing those parameters is realistically impossible. Therefore, the managers just depend on empirical methods to design the system without performance evaluation until now even though planning how to design the system is critical to initialize aquaculture. However, the detailed assessment is essential to ensure RAS operates well as intended as we mentioned earlier to achieve the goal of smart aquaculture.

We adopt computational fluid dynamics (CFD) to analyze the flow characteristics of RAS according to the design parameters to handle this problem. CFD is a category of fluid mechanics which analyzes fluid flow based on computer simulation. As the sophisticated boundary conditions are defined, CFD can reflect real-world phenomena since the simulation satisfies the laws of conservation in fluid mechanics [24]. To the best of our knowledge, this paper firstly tries to handle RAS modeling and analyzing the water treatment performance considering the design parameters.

The main contributions of our work are as follows:

- We adopt RAS tank design parameters widely used in aquaculture industry and present the detailed tank design structure so that CFD can reflect real-world scenario.
- We analyze the water treatment performance including the behavior of water in the tank and the solid particle removal rate according to the design parameters without actual operation which costs high.
- Analysis is performed on complex multiple-tanks structure by extending the simple single tank structure.

In this paper, we focus on the analysis of the circular water tank. The remainder of this paper is organized as follows. In section 2, a system model of RAS including design parameters for the water tank and modeling parameters for solid particles are illustrated. In section 3, we analyze the water fluidity and solid particles elimination rate of the water tank based on CFD using the configured parameters before concluding this paper in section 4.

2. RAS design considerations

2.1 Water tank design parameters

To analyze the flow properties of a water tank with CFD, the geometry of the water tank should be designed first. For this purpose, we configure the design parameters of the RAS tank which are widely used in physical tanks to reflect on a real aquaculture field in **Table 1**. Once the tank is designed, the physical parameters are not controllable while the flexible parameters can be handled by external users. The detailed geometry is depicted in **Fig. 2**. In addition, we also further consider an environment in which three water tanks are serially connected which is shown in **Fig. 3**. The volume mesh of the water tank component is illustrated in **Fig. 4**.

For CFD simulation, an inlet mass flow rate should be calculated. The inlet mass flow rate means the amount of water that moves through inlet. Thus, the total water weight in the tank and rotation rate should be considered to calculate the inlet mass flow rate. Firstly, according to the design parameters, the water volume V in the tank can be derived as follows:

$$V = \pi \times (tank\ radius)^2 \times (tank\ height) = \pi \times (2m)^2 \times 0.6m \approx 7.53\ m^3. \quad (1)$$

Then, the total water weight in the tank W is calculated as follows:

$$W = V \times (water\ density) = 7.53\ m^3 \times 997\ kg/m^3 = 7507.41\ kg. \quad (2)$$

When the unit time of the flow rate is set to the second, the inlet mass flow rate can be calculated as follows:

$$Inlet\ mass\ flow\ rate = W \times (rotation\ rate) = \frac{7507.41\ kg \times 36}{24\ \times 3600s} = 3.128\ kg/s. \quad (3)$$

Since the calculated value in (3) is the result per one water tank, when multiple tanks are connected, the inlet mass flow rate is multiplied by the number of tanks. Moreover, we can notice that once the physical design parameters like tank shape, tank radius and inlet hole diameter are determined, the inlet mass flow rate is only affected by flexible parameters.

Table 1. RAS tank design parameters

Parameter name	Value	Property
Tank shape	Circular	Physical
Tank radius	2 m	Physical
Tank height	1.2 m	Physical
Water height	0.6 m	Flexible
Inlet hole diameter	100 mm	Physical
Outlet hole diameter	100 mm	Physical
Tank floor slope	0 degree	Physical
Rotation rate	36 times / day	Flexible
Inlet angle	0 degree	Physical
Water density	997 kg/m^3	Physical

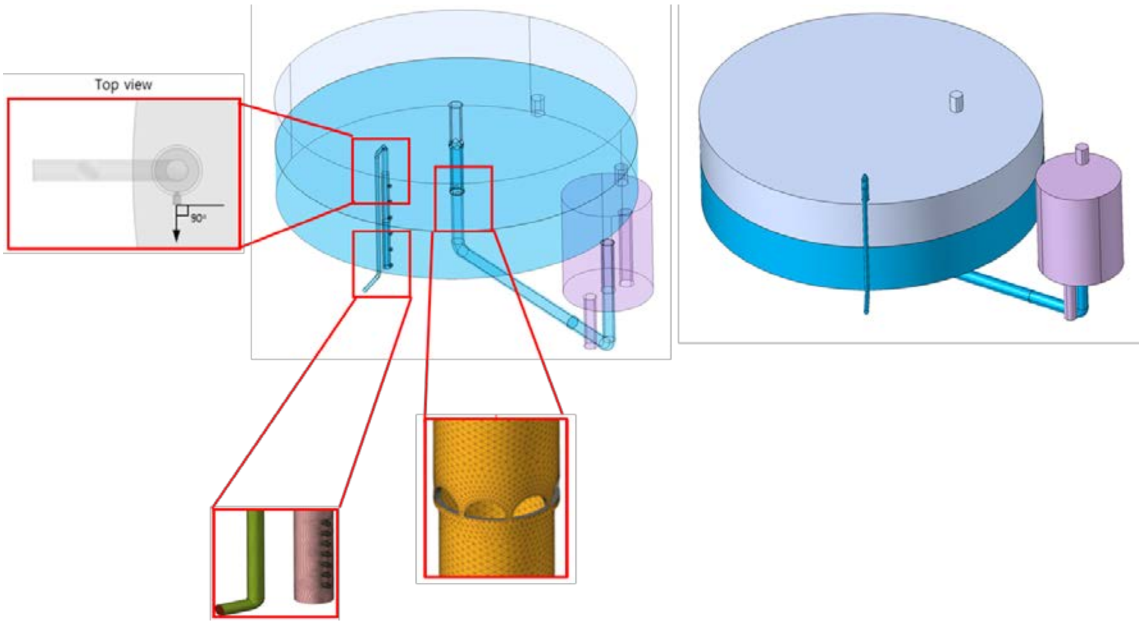

Fig. 2. Geometry of a single circular water tank

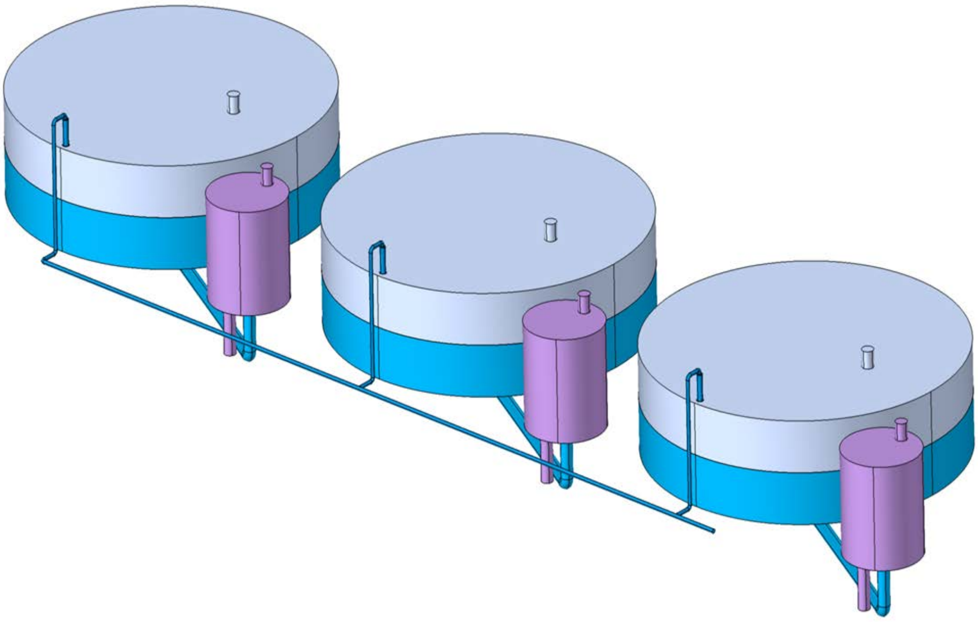

Fig. 3. Geometry of the multiple water tanks

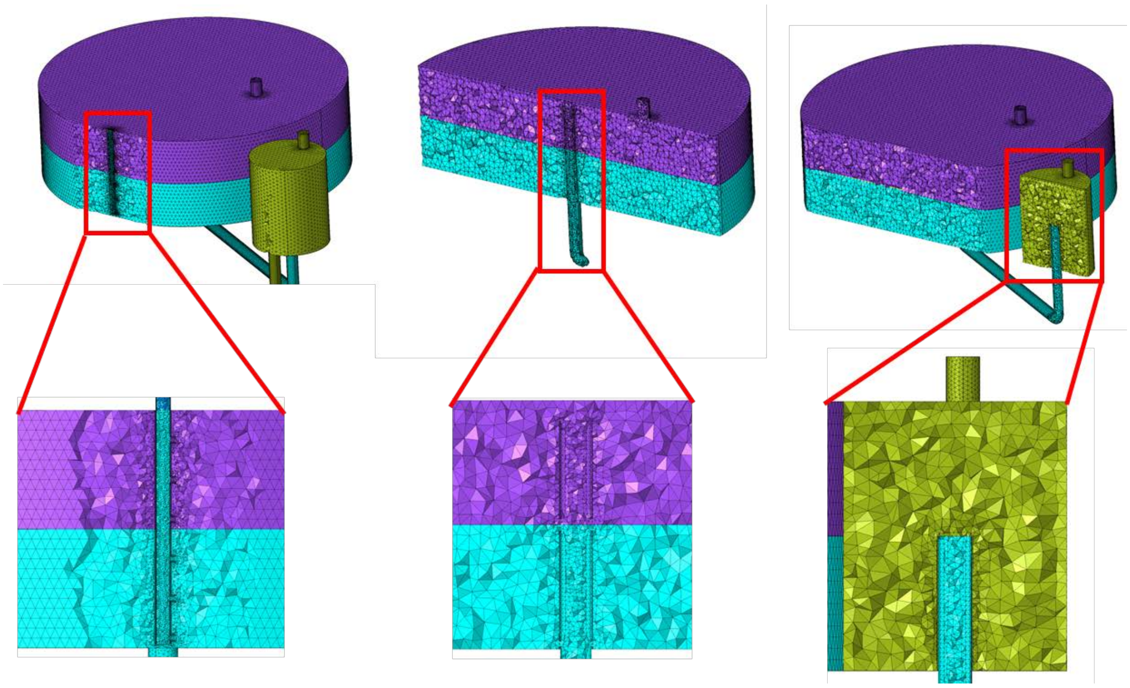

Fig. 4. Volume mesh of water tank component

2.2 Solid particle modeling parameters

In RAS, solid materials such as the excretion of waste products and redundant dry feeds need to be eliminated through outlet holes to maintain proper nurturing conditions. **Table 2** summarizes the modeling parameters of the solid particles to configure movement properties. We consider two types of particles having different densities. One type of particles has a density lower than water and the other type has a density higher than water for analyzing the fluidity properties according to the density.

Each particle consists of two viscous spherical substances designed by the discrete element method (DEM). Moreover, individual particles are generated in the center of the water tank according to **Fig. 5**.

Table 2. Solid particle modeling parameters

Parameter name	Value
Cohesive surface energy	4 J/m^2
Density of particle 1	940 kg/m^3
Density of particle 2	1050 kg/m^3
Density of water	997 kg/m^3

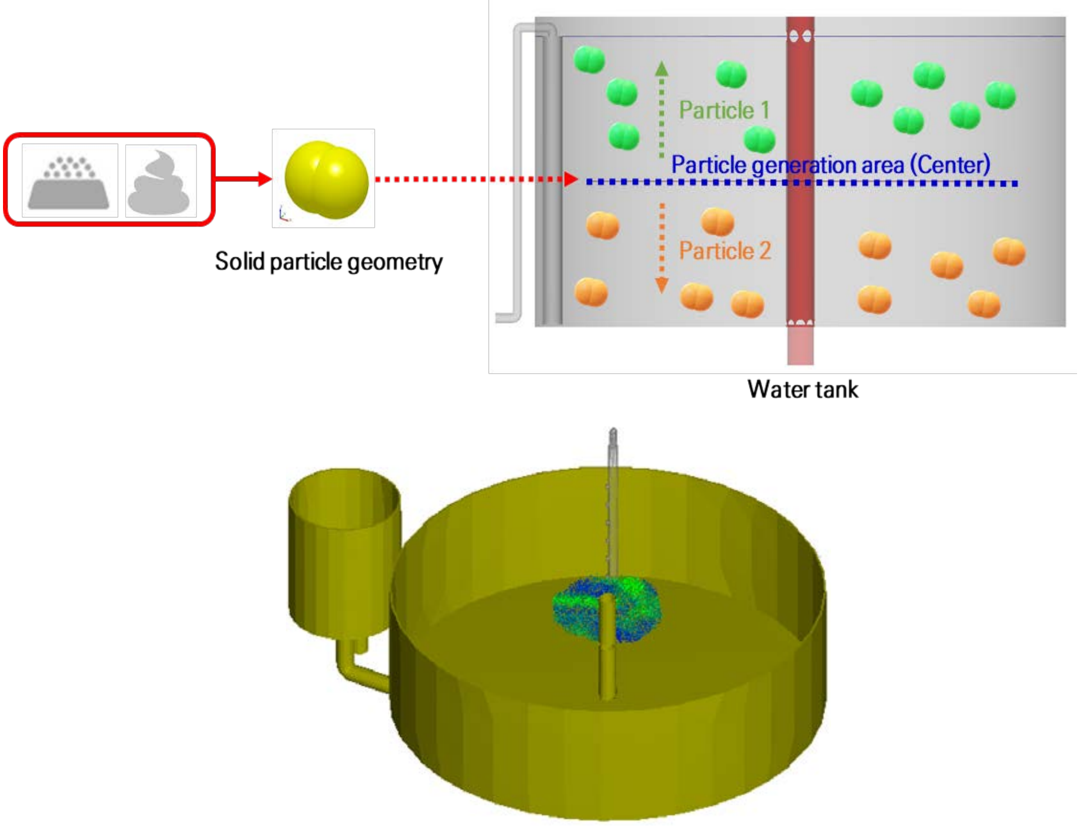

Fig. 5. Solid particles geometry and generation in the water tank

3. CFD simulation results and analysis

In this section, we analyze the water fluidity and the removal rate of solid particles based on CFD according to the parameters described in section 2.

3.1 Single water tank CFD results

Through CFD with the RAS design parameters in **Table. 1**, water fluidity in the tank is automatically measured according to the fluid mechanics [24]. Three-dimensional (3D) streamlines according to the velocity magnitude viewed from different angles of the tank are depicted in **Fig. 6**. Each line represents the water flow. The color of the line is closer to red, the faster the flow rate. In contrast, the color of the line is closer to blue, the slower the flow rate. As expected, the water speed is the fastest near the inlet of the water tank. Interestingly, we also find there is a region where the water speed is very slow. In order to check more specifically, we carry out an iso-surface analysis under the condition of very low velocity magnitude 0.05 m/s. The iso-surface analysis shows a surface of constant value. The result of iso-surface analysis is illustrated in **Fig. 7**. From **Fig. 7**, we can check more specific surface where the water speed is extremely slow illustrated as blue lines in **Fig. 6**. Consequently, we confirm there exists a region with nearly ‘0’ velocity magnitude so-called ‘dead zone’ formed near the center of the tank.

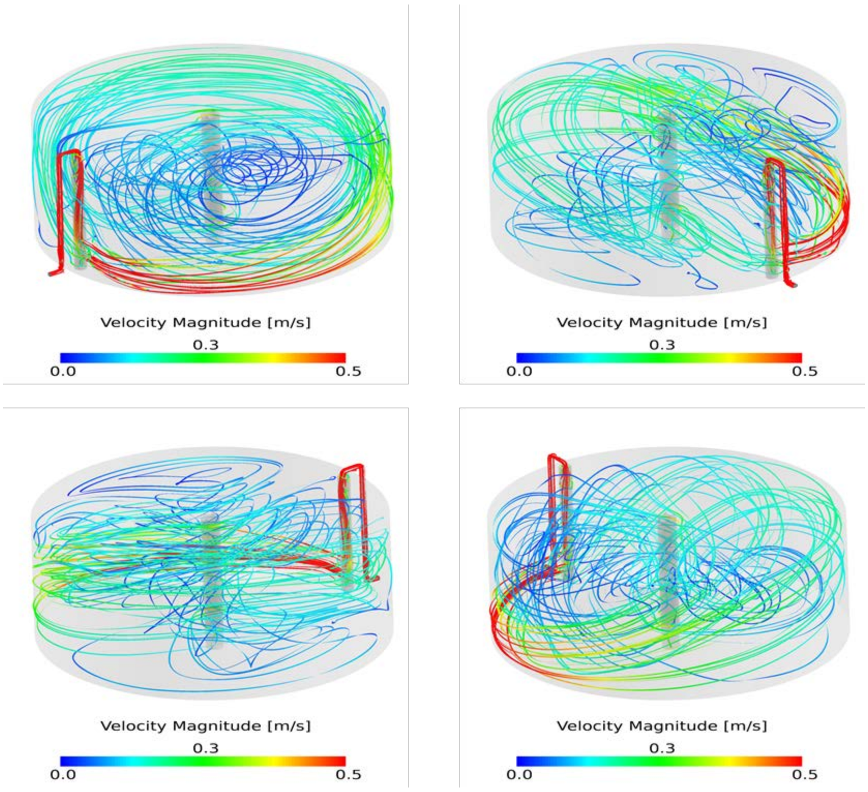

Fig. 6. 3D streamlines of velocity magnitude of the circular water tank

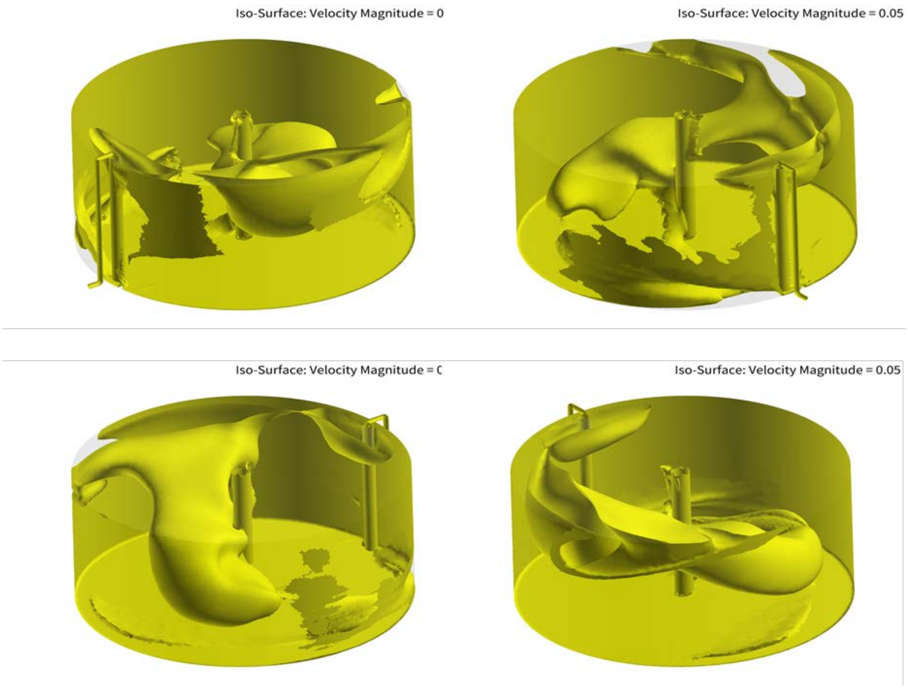

Fig. 7. Iso-surface analysis of velocity magnitude of the circular water tank

Another simulation is performed for 1200 seconds after the generation of particles to check the elimination performance of solid particles. Since we configure the water rotation rate as 36 times/day, the results show the particle elimination efficiency during a half rotation. We generate total 10000 particles, 5000 high density particles and 5000 low density particles each to generalize removal rate in the real aquacultural world which creates large number of particles in the water tank. **Fig. 8** shows the elimination efficiencies of the particles in the tank during simulation. In the early stages of the water cycle, the particles are rarely removed regardless of the density. After a certain amount of time has elapsed, we can check the particles begin to be eliminated. Moreover, the removal efficiency is greater when the density of the particles is small. This is because particles having lower density have high speed, so they can reach relatively easily to the outlet holes.

To specifically analyze the particle's movement property in the water tank, we plot the average speed of the particles in **Fig. 9**. As shown in **Fig. 9**, the initial average speed is relatively slow since recirculation effect is not reflected, but the average speed becomes getting faster as time elapses. From **Fig. 8** and **Fig. 9**, we can check the timing at which particles are removed coincides with the timing when the speed of the particles peaked. Several particles experience fluctuation and flow out of the tank. As particles with high speed is removed, the average speed also decreases. From this result, we can also figure out the particles with low density undergo the fluctuation for a longer period of time compared to those with high density. This can explain why the particles having low density are more easily eliminated than particles having high density.

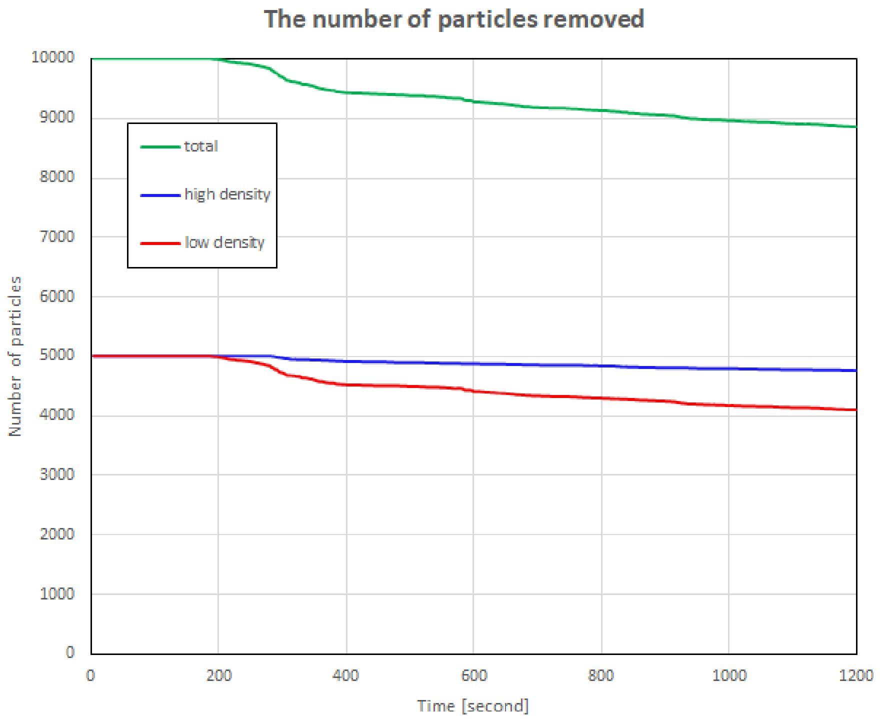

Fig. 8. Particle removal efficiency of the single water tank

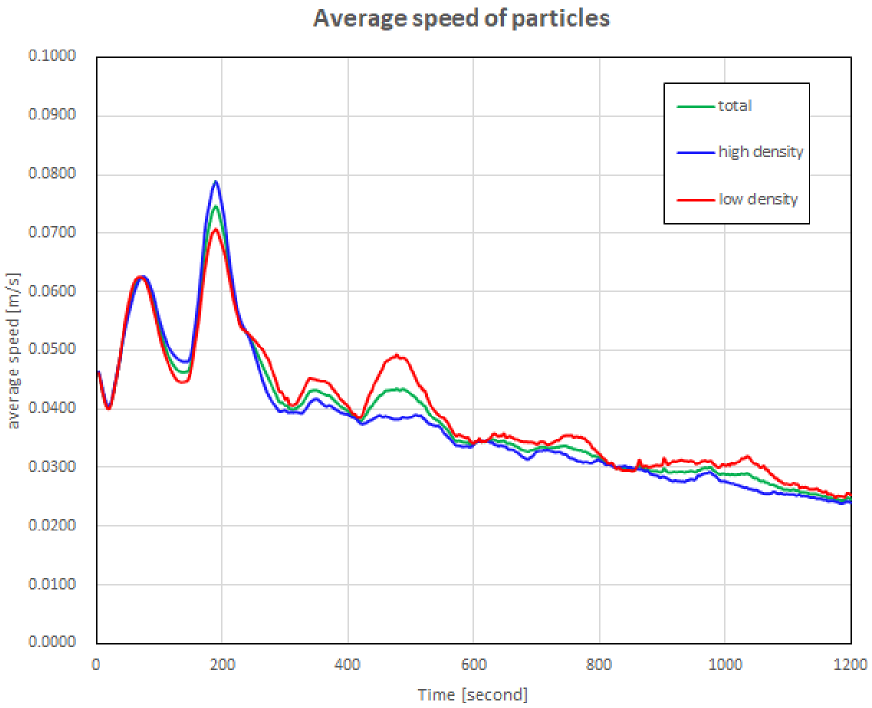

Fig. 9. Average speed of particles in the single water tank

3.2 Multiple water tanks CFD results

In this subsection, we consider the case that three water tanks are serially connected. As explained in section 2, the inlet mass flow rate becomes tripled compared to the case of the single water tank.

Firstly, we show the top view of 3D streamline of each water tank in **Fig. 10** similar to the single water tank case. From **Fig. 10**, a similar trend as in the single water tank case can be observed, which means the water speed is the fastest near the inlet while there exists nearly ‘0’ speed region near the middle region for three water tanks. However, we can check the first tank’s velocity magnitude is relatively small compared to other two tanks. In order to find the reason of this phenomenon, we analyze the surface pressure of each water tank in **Fig. 11**. From this result, we can find the hydraulic pressure increases as the farther from the first tank. Therefore, the difference in these pressures leads to the result in **Fig. 10**, which means the inlet mass flow rate is not equivalently distributed to each tank even though we compensate the value of the inlet mass flow rate considering the number of the water tanks.

In the second simulation, we analyze the particle eliminate performance of each water tank for 3600 seconds after the generation of particles. For each tank, the total number of generated particles is 10000. Since it was confirmed that the elimination tendency according to the particle density was similar to the single water case that particles with low density are easily flowed out, we present the removal performance regardless of the density according to the water tank. **Fig. 12** shows the removal efficiencies of the particles for three water tanks. At the beginning of the simulation, few particles are flowed out regardless of the water tanks. As time passed fluctuation occurred and the particles started to be removed for all three water tanks.

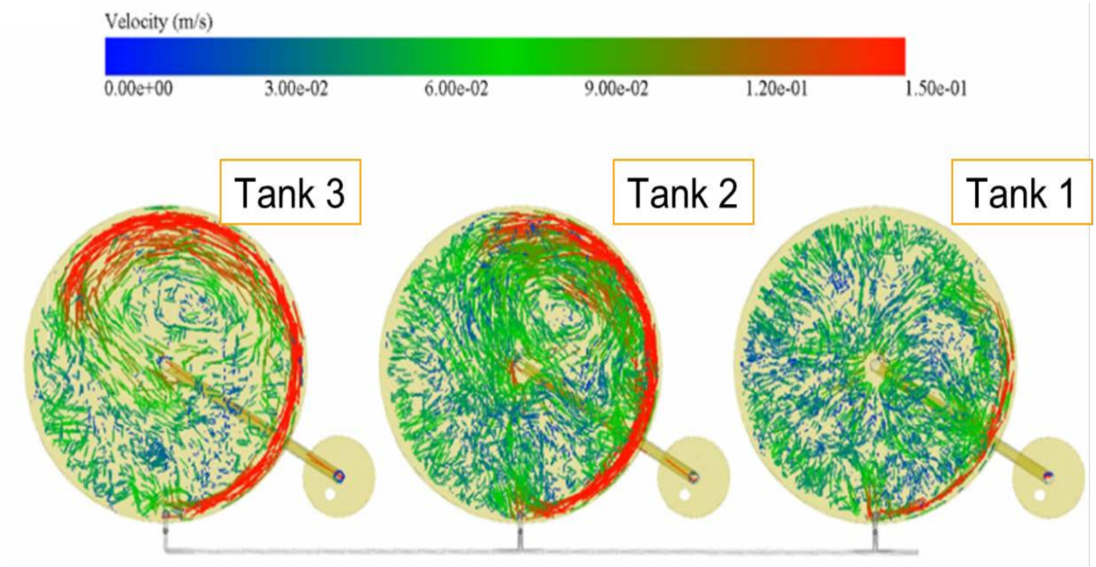

Fig. 10. 3D streamlines of speed of the serially connected three water tanks

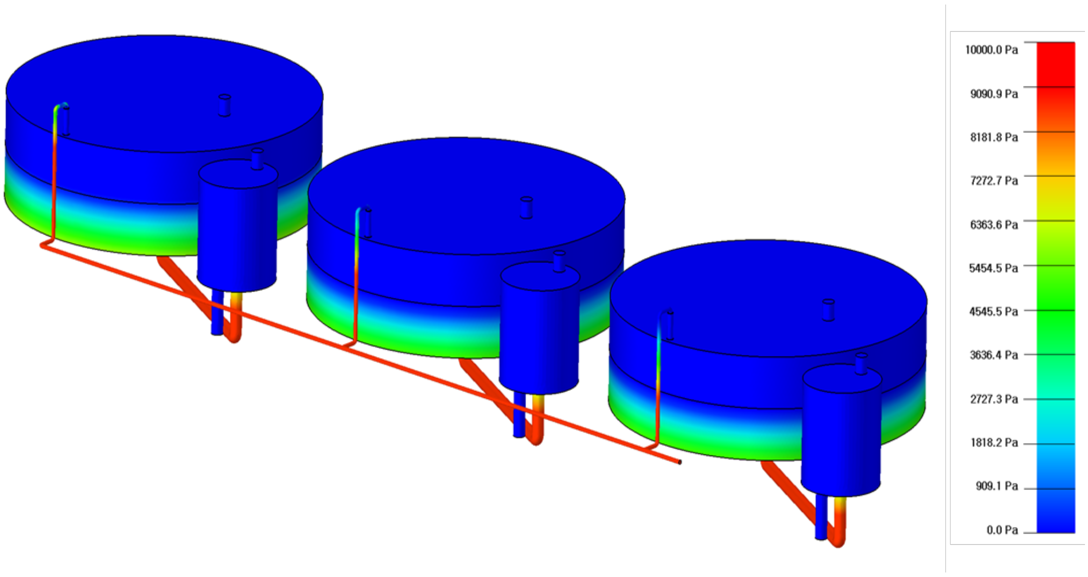

Fig. 11. Surface pressure of the serially connected three water tanks

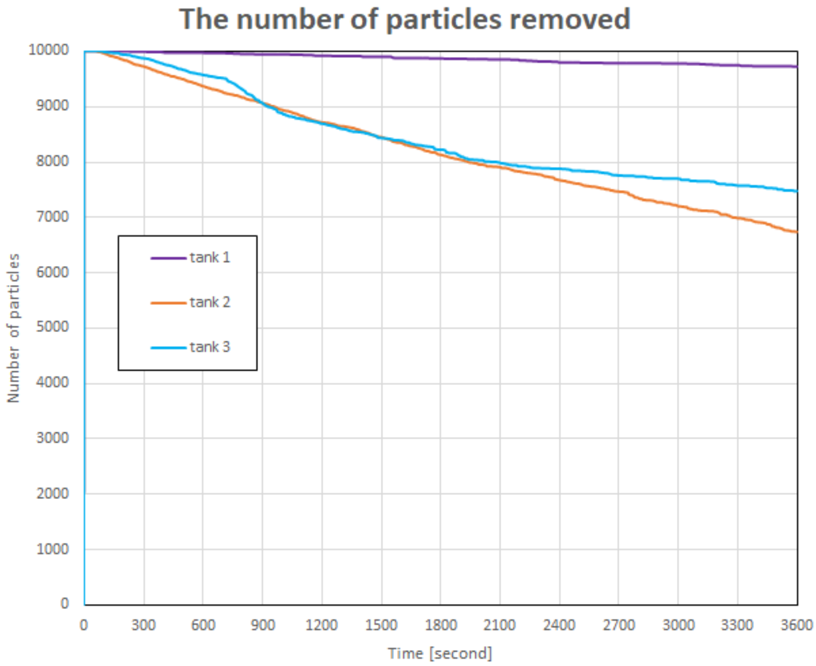

Fig. 12. Particle removal efficiency of the serially connected three water tanks

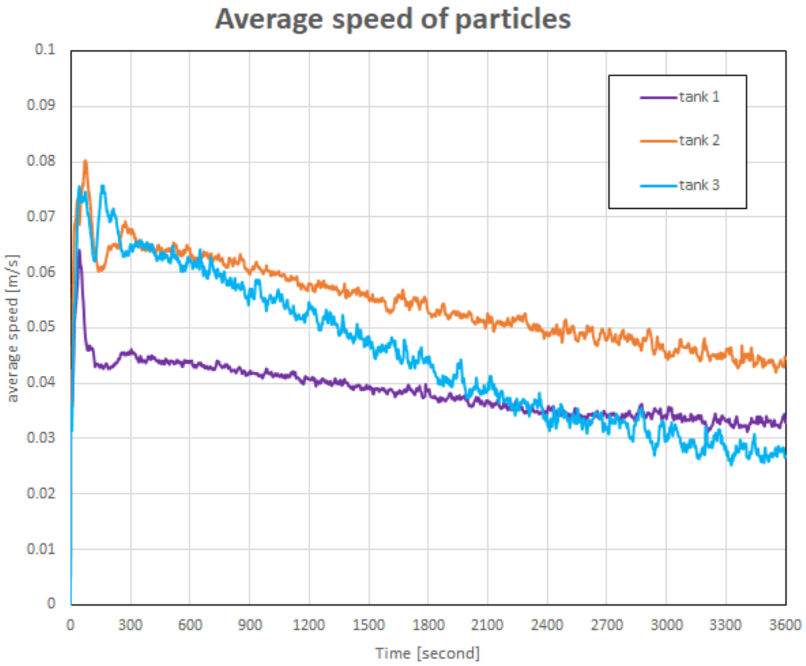

Fig. 13. Average speed of particles in the serially connected three water tanks

However, we can check the number of eliminated particles is different according to the water tank. For the tank 1, the particle removal performance is significantly inferior compared to the other tanks. This is because the tank 1's water circulation does not occur well as seen in **Fig. 10**, so most of particles can't be flowed out to outlet holes. In contrast, tank 2 and tank 3 have almost the same performance for 2000 seconds. After that, particles in tank 2 are steadily removed but those in tank 3 reach saturation. From this result, we can conclude that the water speed should be neither too fast nor too slow in order to efficiently eliminate the particles. **Fig. 13** shows the average speed of the particles in each tank. We can also check that the particles in the tank 2 maintains a moderate speed compared to the other tanks, which leads to the best particle removal efficiency.

4. Conclusion and future work

In this paper, we performed the CFD simulation on a circular water tank used for RAS to analyze the water treatment performance. The water treatment performance is crucial consideration for the RAS design and heavily contingent upon the flow characteristics. However, many variables are consisting of RAS design parameters so the flow characteristics are difficult to analyze. With the aids of CFD, we analyzed the water fluidity and the solid particle removal efficiency. We considered the RAS tank model used in the actual aquaculture field. The simulation was carried out for both a single water tank and serially connected three water tanks cases. From the water fluidity CFD simulation results, we could find the dead zone region with very low water speed is formed in the water tank. Moreover, from the removal efficiency of solid particles simulation results, we confirmed the particles with low density is more easily flowed out through the outlet holes compared to the particles with high density. This is because low density particles had a higher speed in the water tank, which provides the higher probability to be eliminated through the outlet holes. For multiple water tanks experiment, overall trends were similar with a single water tank case. However, the important result was also found that the inlet flow rate was not evenly distributed to each tank so differences occurred in the water fluidity and the degree to which particles are removed. We conclude following several items to be considered for the efficient RAS design.

- Configuration of design parameters for reducing the dead zone
- Configuration of design parameters for enhancing to remove the solid particles
- Configuration of design parameters to distribute inlet flow rate equally to multiple tanks

Until now, not only does it cost too much to analyze the water treatment performance but also the controllable parameters are restricted after the physical water tank is designed. However, we provided the possibility that the CFD based RAS design and analysis on the virtual environment can reduce the cost in this paper. In the future work, we will design RAS with more various tank design parameters and analyze the water treatment performance based on CFD. Firstly, we will fix the physical tank design parameters while varying the user-specific parameters. Next, we will repeat above procedure after changing the physical values. Finally, we will compare the performance according to the different parameters. After lots of simulation results are accumulated, we expect that numerical analysis for water treatment performance also could be possible.

We expect that the digital twin technologies could help to find an optimal combination of the RAS design parameters for the efficient water treatment. After applying the digital twin technique, we will check how the technology fits with CFD based results.

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