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Hydrodynamics of octagonal culture tanks with Cornell-type dual-drain system

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ABSTRACT

Large culture tanks of several hundred or thousand m^3 size are generally encouraged for economic advantages in Recirculating Aquaculture Systems (RAS). Out of numerous possibilities in designing the inlet and outlet configurations in octagonal culture tanks, the inlet pipes near the corner walls and the outlets at the tank's center and/or on side wall are some of the widely-used configurations. The use of wall drain to achieve a controlled flow pattern in the tank, however, influences distinct flow features such as pressure, velocity, uniformity and turbulence in the tank, which are of theoretical interest as well as practical importance. A finite volume description of the flow in an octagonal culture tank at full-scale was therefore developed using Realizable turbulence model with second order accuracy in space and time. The tank was equipped with an inlet pipe near the corner wall and dual-drain outlet system of Cornell-type. The base case had a flow configuration of 45% of flow through central bottom drain, and the rest through the wall drain. Model verification was performed using grid convergence tests, and validation was conducted using Acoustic Doppler velocimetry (ADV) based velocity measurements. The effect of wall drain on the large-scale and small-scale turbulent structures was studied using the distribution of turbulent kinetic energy and vorticity respectively. The parametric study on the flow-split between the two outlets was analyzed using different flowfield indicators, such as flow velocity, uniformity, vorticity strength, maximum absolute vorticity and swirl number. Such an inclusive analysis not only explores the hydrodynamics in the commercial culture tanks with Cornell-type dual-drain but also recommends the farmers with the suitable flow-split between such outlet systems.

1. Introduction

In the seeking of disease prevention, increased production rates and environment preservation, Recirculating Aquaculture Systems (RAS) have been in limelight to exercise a controlled rearing system (Dalsgaard et al., 2013; Summerfelt et al., 2016). In addition to creating a healthy environment, it is possible to exert some control over the flow domain in circular-type tanks used RAS facility, which plays a critical role in fish growth and hence the production and financial benefits. Previous studies have determined that the rotational velocity about the perimeter of circular tanks is strongly dependent upon the impulse force of water flow injected tangentially into the circular-type tank (Tvinnereim and Skybakmoen, 1989; Paul et al., 1991; Davidson and Summerfelt, 2004; Oca and Masalo, 2013; Venegas et al., 2014; Plew et al., 2015; Prabhu et al., 2017; Gorle et al., 2018). Thus, rotational velocity depends upon the hydraulic exchange rate and inlet orifice velocity (dependent on orifice number, open area, and flow rate) and direction produced at the flow inlet structure(s). In contrast, rotational velocities close to the center of circular-type tanks are associated with the impulse force exiting the center of the tank, i.e., dependent upon the surface loading rate at the center drain (Davidson and Summerfelt, 2004). The inlet and outlet impulse forces are balanced by the forces created by drag on the fish and tank walls and floors (Plew et al., 2015).

The recommended hydrodynamic state of a culture tank comprises not only the sufficient rotational velocity, but also proper mixing through the occurrence of primary and secondary vortices that ensure the desired water quality. Non-uniform distribution of rotational velocity (Oca and Masalo, 2007), non-homogeneous water quality (Saba and Steinberg, 2012), and unsteady distribution of biosolids are some of the natural and undesirable phenomena occurring in culture tanks. Although there is an influence of tank geometry on the overall flow pattern (Duarte et al., 2011), the flow boundary conditions have a phenomenal impact on the hydrodynamics in the bounded space of the culture tank. Several practical methods have been tried to control the flow in the culture tank. A simple and widely adopted practice in creating a uniform inflow is to use a multiple nozzle configuration on

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the inlet pipe. Oca et al. (2004) made improvements in the inlet and outlet designs to achieve the desired flow pattern in the rectangular culture tanks. The standard practice of single inlet-outlet combination, however, cannot offer a controlled flow solution that meets the flow rotationality and uniformity requirements. Instead, researchers have attempted to create adaptable boundary conditions for improved hydrodynamics (Venegas et al., 2014). Several passive flow control methods have been tested and used in the past research, which included adjustable orientation of inlet structures (Davidson and Summerfelt, 2004; and Summerfelt et al., 2004, 2006, 2009a), and baffles for better mixing of the flow (Masalo and Oca, 2014). A celebrated method is to use a multiple drain system, where more than one outlet are used at appropriate locations, to achieve desired flow conditions in the tank. In a dual-drain system with an elevated wall-drain, the solids can quickly be discharged out of the tank and improve the water quality. Also, such wall drain can reduce the flow velocity downstream and hence control the flow pattern as desired.

Although octagonal tanks are the best alternative for circular tanks with an advantage of better space management and shared sidewalls, it is important to note that there is a considerable difference between the two tank shapes as the flow velocity and water quality is concerned (Gorle et al., 2018). For instance, dead zones can be created in the near-corner wall region in the octagonal tanks, which does not happen in case of circular tanks. Circular-type culture tanks sometimes use dual-drain to create two advantages over a single drain tank, i.e., to concentrate a majority of settleable solids into a relatively small tank underflow (as in a swirl separator) and/or to shift the impulse force associated with outlet flows in a manner that can be used to help optimize water rotational velocities located in the annular region about the center of the tank (Davidson and Summerfelt, 2004; Gorle et al., 2018). Water rotational velocities, particularly within the annular region about the tank center, are critically important to create a self-cleaning tank and when trying to maintain more optimum swimming speeds for the fish. At least one drain is always located to draw flow off the bottom center of the tank. However, the second drain is typically located above the bottom-drawing drain at the tank's center (Terjesen et al., 2013) or part-way up the tank's side wall (Davidson and Summerfelt, 2004; Summerfelt et al., 2004; Despres and Couturier, 2006; Summerfelt et al., 2006; Summerfelt et al., 2009a, 2009b; Wolters et al., 2009; Pfeiffer and Riche, 2011; Carvalhoa et al., 2013; Terjesen et al., 2013; Summerfelt et al., 2016). The second drain is elevated in order to withdraw flow out of the tank in a location where it should contain minimal settleable solids, because the settleable solids tend to concentrate on the tank floor as they are moved by the tank's primary rotating and radial flows to the bottom-center drain. However, the lack of knowledge on the effect of elevated wall drain on the overall flow behavior leads to uncertain flow split ratio in the commercial as well as research facilities, which describes the paucity of research on culture tanks with dual-drain systems. Only three studies have described empirical water velocity data collected in sidewall-type dual-drain circular tanks (Davidson and Summerfelt, 2004; Summerfelt et al., 2006; Summerfelt et al., 2009a). This results in a trial-error flow-split between multiple outlets, or sometimes uncertain operating conditions in the commercial farms.

The problem of hydrodynamics in a culture tank with a single outlet at the central bottom location and tangential inflow can be viewed as the combination of rotating flow in a container that creates circular flow and vertical motion of the flow towards the outlet. Numerous theoretical and computational studies were conducted on these two cases separately in different applications, which are useful in understanding the basics of flow behavior. The case of bathtub vortex is analogous to the vertical motion of the flow in the culture tank, with throttle opened central bottom drain. The twisting air bubble swiftly penetrates into the deformed free-surface and attempts to reach the outlet at higher rotational speeds (Klimenko, 2001; Andersen et al., 2003; Mizushima et al., 2014). However, the continuous replenishment of water into the tank controls the deformation of water surface (Meshkov and Sirotkin, 2013). A relatively stable water surface can be maintained with a steady inflow rate so that the water level remains flat as well as constant. This practice simplifies the computational modelling by assuming the water surface as a stress-free boundary. Nonetheless, the additional outflow through elevated wall drain wall drain considerably influences the flowfield. Kawahara et al. (1997) observed the multiscale interactions between small-scale vortical structures that tend to wrap around the large-scale vortex column due to the local strain field. However, no research in this direction has been done on culture tank hydrodynamics.

Axisymmetric draining flow with an ideal setting of tangential inflow and central bottom outlet is apparently similar to that in a rotating tank. Flow in a stirred tank, which is predominantly tangential, was recently studied by Lane (2017) using CFD, while the particle motion in the similar systems were investigated by Bashiri et al. (2016). Particles of a wide range of size critically determine their distribution in the flowfield due to the differences in their angular velocity although the mean rotation of the flow is constant. This holds true in the case of culture tanks as well. Particles' morphology is supposed to be affected due to the shear force. When applied to fish tanks, this phenomenon is detrimental as breakup of biosolids deteriorates the water quality (Couturier et al., 2009). Improving the flow uniformity is one of the ways to reduce the extra shear on the particles in a culture tank. But, the effect of splitting flow through a center and sidewall dual-drain outlets on the flow uniformity as well as turbulence is an unexplored topic.

High-fidelity modelling, whereby the turbulent motion is resolved at high resolution using computational tools, has been a promising approach to obtain a better insight into the hydrodynamics, and thus make decisions on design improvement and optimization. Recent studies on computational modelling of hydrodynamics in a closed sea cage (Klebert et al., 2018) used unsteady Reynolds Averaged Navier-Stokes modelling to analyze the flowfield, and particle dispersion and flushing. Kim et al. (2015) performed the CFD analysis of cage systems to evaluate the flow pattern and dissolved oxygen distribution. The large eddy simulations of Salmon net cage was performed by Cornejo et al. (2014) to assess the wake dynamics and passive tracer advection in the domain. Veerapen et al. (2005) employed CFD to analyze the removal of waste solids using swirl separators.

In this study, the hydrodynamic response of a commercial culture tank as a function of flow-split between central bottom outlet and elevated wall drain was investigated using 3D CFD modelling at full-scale. Velocity measurements at discrete locations in the tank using Acoustic Doppler Velocimetry (ADV) were used to validate the computational model. Unlike the aforementioned studies, which were largely limited to the examination of global flowfield, the present study focused on the evolution of large-scale and small-scale turbulent flow structures and the effect of dual-drain system on them. Vortical field of the tank was computed using Q-criterion. Furthermore, non-dimensional flowfield indices were formulated using surface integrals to quantify the effect of dual-drain operation on the characteristics of velocity, uniformity, vortex strength, maximum circulation and swirling in the tank.

2. Recirculating Aquaculture System (RAS) tank under study

This study considered one of the nine octagonal RAS tanks at Nofima Centre for Recirculation in Aquaculture (NCRA) in Norway. The research facility was constructed to address a number of issues related to water quality, fish growth, hydrodynamics, etc., and produce an expected 480,000 smolts annually. All RAS tanks are identical in design, dimensions and equipment. To study the effect of dual-drain on the tank hydrodynamics, one of the octagonal tanks at regular operating conditions was considered in the present research. The basic dimensions of the tank are described in Fig. 1. The 100 m^3 sized tank has