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Water velocity in commercial RAS culture tanks for Atlantic salmon smolt production

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ABSTRACT

An optimal flow domain in culture tanks is vital for fish growth and welfare. This paper presents empirical data on rotational velocity and water quality in circular and octagonal tanks at two large commercial smolt production sites, with an approximate production rate of 1000 and 1300 ton smolt/yr, respectively. When fish were present, fish density in the two circular tanks under study at Site 1 were 35 and 48 kg/m^3, and that in four octagonal tanks at Site 2 were 54, 74, 58 and 64 kg/m^3, respectively. The objective of the study was twofold. First, the effect of biomass on the velocity distribution was examined, which was accomplished by repeating the measurements in empty tanks under same flow conditions. Second, the effect of operating conditions on the water quality was studied by collecting and analysing the water samples at the tank's inlet and outlet. All tanks exhibited a relatively uniform water velocity field in the vertical water column at each radial location sampled. When fish were present, maximum (40 cm/s) and minimum (25–26 cm/s) water rotational velocities were quite similar in all tanks sampled, and close to optimum swimming speeds, recommended for Atlantic salmon-smolt, i.e., 1–1.5 body lengths per second. The fish were found to decrease water velocity by 25% compared to the tank operated without fish. Flow pattern was largely affected by the presence of fish, compared to the empty tanks. Inference reveals that the fish swimming in the tanks is a major source of turbulence, and nonlinearity. Facility operators and culture tank designers were able to optimize flow inlet conditions to achieve appropriate tank rotational velocities despite a wide range of culture tank sizes, HRT's, and outlet structure locations. In addition, the dissolved oxygen profile was also collected along the diametrical plane through the octagonal tank's centre, which exhibits a close correlation between the velocity and oxygen measurements. All tanks were operated under rather intensive conditions with an oxygen demand across the tank (inlet minus outlet) of 7.4–10.4 mg/L. Estimates of the oxygen respiration rate in the tank appears to double as the TSS concentration measured in the tank increases from 3.0 mg/L (0.3 kg O_2/kg feed) up to 10–12 mg/L (0.7 kg O_2/kg feed). Improving suspended solids control in such systems may thus dramatically reduce the oxygen consumption and CO_2 production.

1. Introduction

The aquaculture industry shows a strong and growing interest in recirculation aquaculture systems (RAS; Verdegem et al., 2006; Martins et al., 2010; Dalsgaard et al., 2013; Summerfelt et al., 2016). Such facilities have only minimal direct hydraulic connection with the environment, and RAS can capture over 98% of the fish waste solids (Chen et al., 2002; Summerfelt and Vinci, 2008). RAS allows for greater control of the rearing environment than cages in sea, and makes avoidance of parasites, and nutrient reclamation possible (Summerfelt et al., 2016). Since 2012, when the Norwegian Ministry of Fisheries allowed hatcheries to produce larger smolt or post-smolt up to 1000 g in tanks on land or in the sea, the Norwegian industry has been investing or considering optimal timing to undertake an investment in post-smolt production facilities (Hagspiel et al., 2018). And, over the last five years, Norwegian Atlantic salmon farmers have expanded smolt and post-smolt production using RAS technology (Summerfelt et al., 2016); recent tanks are typically large (500–3300 m^3 per tank) and operate with relatively short tank hydraulic retention times (HRT), tend to produce better water quality than older tanks with longer HRT due to lower metabolic loading per unit of flow. However, the hydrodynamic behaviour of large RAS tanks is vulnerable to the inherent turbulence, prevailing in large circular and octagonal tanks. Note that octagonal tanks, like circular tanks, can be advantageous because they can be

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nested together to conserve floor-space and can share common walls to reduce concrete costs; they also provide similar hydrodynamic benefits/challenges with their circular rotating flow and internal mixing. However, the free-surface effects and the turbulence generated at the air-water interface may also lead to an intrinsic uncertainty in the flow pattern. In addition, continuous and non-linear interaction between the water currents and the fish biomass is another source of non-uniform flow conditions throughout the tank. One of the effects of turbulence on the tank with fish is enhanced mixing, which results in variations in the velocity profile and resistance to flow circulation (Lunger et al., 2006; Masalo et al., 2008; Plew et al., 2015). Optimizing the culture tank environment is essential for achieving fish culture success, because much of a fish farm's fixed capital costs – such as culture vessels, building foot-print, fish feeders, oxygen probes, flow or level switch – and variable costs – such as fish, fish feed, labour, disease treatments, water quality monitoring expendables, water pumping, and water treatment requirements – are invested in the culture tank (Timmons et al., 1998; Davidson and Summerfelt, 2004).

The accumulation and distribution of dissolved oxygen (DO) and fish metabolites, such as ammonia and carbon dioxide as well as faecal matter and uneaten feed, can affect Atlantic salmon performance and welfare (Clingerman et al., 2007, Thorarensen and Farrell, 2011; Fivelstad, 2013; Kolarevic et al., 2013; Terjesen et al., 2013; Becke et al., 2017). The production rate, flushing rate, and accumulation of these constituents within the culture environment depends on several factors, including biomass, fish feed rates, system volume exchange, hydraulic retention time, biosolids size and specific gravity, water treatment removal efficiencies, and diverse physio-chemical and hydrodynamic interactions between the solids and flow. In addition, fish swimming behaviour can be influenced by the water quality (Clingerman et al., 2007; Espmark and Baeverfjord, 2009; Davidson et al., 2011b; Good et al., 2018, 2014; Remen et al., 2016). Hence, water velocities, dissolved oxygen concentrations, and dissolved carbon dioxide concentrations can affect the fish distribution, behaviour, and performance across large circular and octagonal culture tanks. Thus, the objective of this study is to describe how water rotational velocities and water quality are distributed across huge commercial salmon smolt tanks. Such an investigation may allow salmon farmers and aquacultural engineers to take steps to improve the hydrodynamic environment of the tank, which can, in the long-term, improve fish performance, welfare and health. This paper presents the empirical investigation performed at two commercial scale RAS facilities for salmon smolt production. While focusing more on the water velocity and dissolved oxygen profile (when possible) along the diametrical plane through the tank's centre, this report also describes water quality parameters measured at the tank's inlet and outlet flows.

2. Material and methods

2.1. Case description

Culture tanks at two smolt farms were selected for sampling based on data collected in a survey by Summerfelt et al. (2016). Visits to two commercial scale smolt production sites were done to measure the flow velocity and dissolved oxygen profiles across representative tanks during commercial operation. The first site was in northern Norway, and the second in North-Western Norway. Table 1 shows the set of empirical studies, performed at the selected sites. Details on the tanks at these sites and the operating conditions during the sampling course are described below.

2.1.1. Site 1: Northern Norway

Site 1 uses two sizes of circular culture tanks; Tank 1 has 12 m diameter which provides 368 m^3 rearing volume and Tank 2 is 16 m in diameter and provides 653 m^3 rearing volume. Total production capacity at the site is 1000 ton/year. The height of all tanks is similar with approximately 4 m depth, and the water column height is 3.25 m. Each tank uses two vertical inlet pipes in the 12 m and 16 m diameter tanks; inlet pipes are asymmetrically placed as shown in Fig. 1. Each tank has a central bottom outlet (80 cm diameter) with a fish exclusion screen that can be lifted by a worker standing on the access platform to flush dead fish. At the time of sampling, the Tanks 1 and 2 were supporting a biomass of 13,031 kg (35 kg/m^3) and 31,215 kg (48 kg/m^3), respectively. In addition, the walkway spans only half of the tank's diameter. Therefore, velocity profiling was possible only for half of diametrical plane. Dissolved oxygen profiling in the tanks was not done at this site. To study the impact of biomass on the velocity distribution, the larger tank at the Site 1 was investigated twice, i.e., once with fish and once without fish.

Table 1
Study matrix, showing the sampling events performed at different tanks in the two sites. Water samples were collected from all the tanks at both sites, but velocity and oxygen profiling were done only in the selected tanks for time and logistics constraints.

		Site 1		Site 2			
		Tank 1	Tank 2	Tank 1	Tank 2	Tank 3	Tank 4
Velocity	Without biomass	✓	✓	✓	✓		
	With biomass		✓	✓			
Oxygen profiling				✓	✓		
Water quality		✓	✓	✓	✓	✓	✓

2.1.2. Site 2: North-Western Norway

Space economy is one of the design criterion often used during the construction of land-based facilities that the aquaculture industry is focusing on. In such instances, octagonal tanks are sometimes used instead of circular tanks to save the building footprint space, up to 15%, while maintaining hydrodynamic features of circular tanks. Octagonal tanks are used at Site 2, which is one of the largest RAS for Atlantic salmon smolt and post-smolt production in the world, with a total production capacity of 1300 ton, i.e. 7.5 million 180 g smolts annually. The water treatment technology allows for reuse of over 99% of the total flow passing through the water recirculating system, i.e., approximately 1% of the pumped through the system represents new make-up water that helps to control accumulation of nitrate when denitrification processes are not incorporated. This 1% is typical for many RAS for salmon smolts in Northern Europe (Terjesen et al., 2013). The measurements of water velocity and quality parameters were performed in four tanks with a rearing volume of 788 m^3. Although the geometric design of all tanks is identical, the biomass properties and the operating conditions of the tanks were different, as listed in Table 2, producing different flow patterns and water quality measurements. Tank flow ranged from 0.21 to 0.26 m^3/s, while number and size of fish in each tank ranged from 184,000 to 300,000 and 162–250 g, respectively. Fish were fed approximately 480–500 kg/d when each tank was sampled, but were withheld from feed during the second visit when two other tanks were sampled.

While the tank height is 4.2 m, the water level was maintained at 3.9 m above concrete floor. All the tanks are equipped with two inlet pipes, each 46 cm diameter. Each inlet has 11 nozzles with diameter 9 cm, which are oriented to create an effective clockwise flow pattern when viewed from top. The flow pattern is antisymmetric along the line of measurement. Dead fish are carried along with the water exiting the tank through four vertical pipes with openings located near the tank bottom centre (Fig. 2); dead fish rise through the vertical pipes with the water flow and are collected at screens located in the top-central outlet while the flow spills into a 90-cm diameter vertical pipe that carries the overflow out of the tank. An over-tank walkway spans each tank close to the tank's centre, which allows workers access required to remove