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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

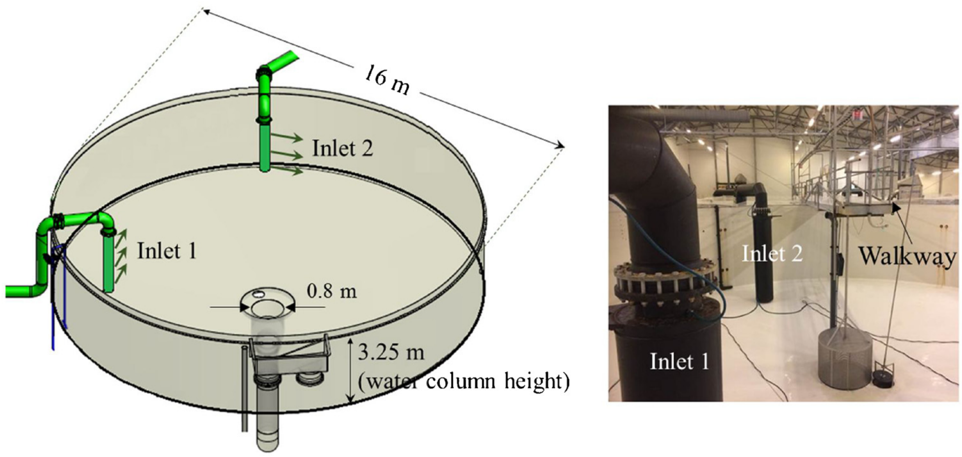


Fig. 1. Basic dimensions of a circular RAS tank at Site 1 (653 m^3). The two inlet pipes are asymmetrically placed, which supply water into the tank in tangential direction (left), and the walkway is placed over only half of the diametrical distance (right).

dead fish from the outlet screen. The walkway also provided access to collect water velocity and dissolved oxygen concentrations at discrete points in a vertical profile across the tank centre. However, this limited the collection of water velocity measurements only along the diametrical plane adjacent to the walkway. Table 2 presents the conditions at which the tanks were operating at both sites on the day of sampling.

2.2. Instrumentation and analyses

Flow rate through the inlet pipes at both sites was measured using a transit-time type, Portaflow 300 ultrasonic flowmeter (Micronics Ltd., Buckinghamshire, UK). Water rotational velocity measurements were collected using a Nortek Acoustic Doppler Velocimeter (Nortek AS, Vangkroken, Norway), which determines the instantaneous velocity vectors of local flow. The Doppler acoustic principle has been used for measuring water velocities by several groups previously, such as by Davidson and Summerfelt (2005), and Masalo et al. (2008). The measuring head of the instrument contains the bistatic acoustic system, which emits short acoustic pulses at a frequency of 6 MHz. The three transducers, placed around the transmitter with 120° azimuth interval, receive the echo, which undergoes digital signal processing in the conditioning module to measure the Doppler shift. This processing module is a low power, standalone component, intended for underwater applications. A data acquisition system was used to convert the analogue signal to digital through RS232 port. The sampling frequency can vary between 1Hz–64 Hz. Although, the sampling frequency should be chosen for the characteristic periods of flow phenomena, which varies according to turbulence intensity and swell characteristics, sampling frequency of less than 32 Hz was found not affecting the quality of the measurements. In some cases, a sampling frequency of less than 4 Hz was found to reduce measurement quality. A value of 8 or 16 Hz was considered for most cases in this study, which produced a correlation greater than 90% and signal-to-noise ratio more than 45 dB. A sampling period of 120 s was set for all test runs to record the velocity components in streamwise (u), lateral (v) and vertical (w) directions. The collected data was processed using ExploreV software (Nortek AS, Vangkroken, Norway) for stationary and transient analysis. An Oxyguard membrane-covered galvanic cell probe was used to measure DO in a profile at Site 2, but logistics prevented its subsequent use at Site 1.

In addition to the velocity profiling, various water quality parameters were measured using different probes and analytical methods. Dissolved oxygen, carbon dioxide, conductivity, pH, TSS, alkalinity, ammonia nitrogen, nitrite nitrogen, and nitrate nitrogen were measured. At Site 1, three samples were collected from each tank inlet and outlet, whereas four water samples were collected from each tank at Site 2. Table 3 shows the list of quantities measured at the two sites and the instrument and methods used to examine the water quality. The maximum measurement uncertainty of Oxyguard probe, Franatech CO_2 sensor and WTW pH electrode are ± 1%, ± 10% and ± 0.03% respectively. All instruments were calibrated and checked with reference standards.

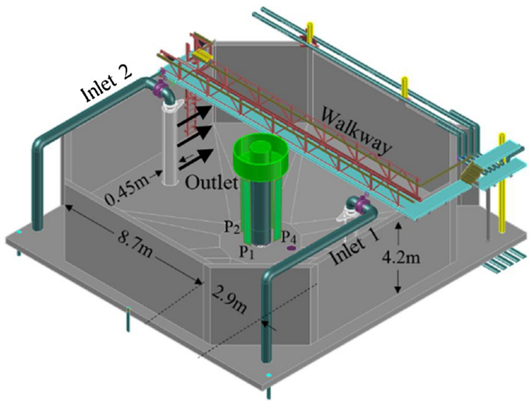
3. Results

3.1. Site 1: Circular tanks in Northern Norway

The water velocity could only be measured adjacent to the walkway, which spanned half of the tank. Therefore, the contour plots shown hereafter represent the velocity distribution from tank's centre (left end of the map) to the wall (right end of the map). Results of

Table 2
Operational conditions of RAS tanks under study. The tanks at Site 1 are circular but different in size, while all tanks at Site 2 are octagonal in shape with equal size of 788m3.

	Site 1		Site 2			
Parameter	Tank 1	Tank 2	Tank 1	Tank 2	Tank 3	Tank 4
Tank shape	Circular	Circular	Octagonal	Octagonal	Octagonal	Octagonal
Volume (m3)	368	653	788	788	788	788
Dia/depth	3.7	4.9	3.6	3.6	3.6	3.6
Flow rate (m^3/min)	16.9	15.6	15.8	12.3	15.8	13.0
HRT (min)	22	42	50	64	50	61
No. of fish	117,609	264,208	197,544	299,898	184,118	312,559
Mean weight (g)	111	118	215	195	250	162
Feed rate (kg/day)	230	378	Fasting at the time of sampling. Latest feed rate was 268	500	Fasting at the time of sampling. Latest feed rate was 287	480
Feed/flow (g/m^3)	9.4	17	12	28	13	26



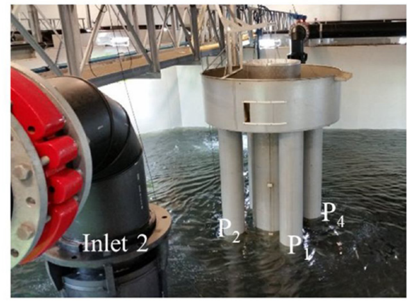


Fig. 2. Geometry and dimensions of the octagonal RAS tank at Site 2. Two inlet pipes deliver the water into the tank, parallel to the nearest wall, as represented by thicker arrows from Inlet 2 (left). Outlet pipes at the centre to exit the water from the tank through central top drain (right). Water was partly drained.

smaller and larger tanks are presented separately.

3.1.1. Tank 1 (368 m^3 in size)

As mentioned in the previous section, the inlet pipes are located asymmetrically, which in turn creates a non-symmetrical flow pattern. Fig. 3 shows the measurement points on the diametrical plane of the tank. The velocity, measured at these 5 × 3 points are interpolated across the plane, and the resulting field is shown in Fig. 4. A steady increase in velocity magnitude is identified from 33 cm/s, near the tank centre, to over 40 cm/s at a radial location 2 m from tank centre. Water rotational velocity then decreased to near 35 cm/s at a radial location of approximately 4 m. The near-wall region of the tank was characterised by a complex velocity field. Near the free-surface and tank's bottom, higher velocities were observed with the lowest near the mid-height region. Non-linear flow distribution and/or fish distribution are possible reasons for this discrepancy.

The maximum cumulative feed burden on Tank 1–operated at a HRT of nearly 22 min − was estimated at 9.4 g feed per cubic meter of water flow on a daily average (Table 2). The oxygen, CO_2, and TSS concentrations measured at the tank outlet were 9.1 ± 0.3 mg/L, 16.4 ± 1.4 mg/L, and 10.0 ± 0.4 mg/L, respectively (Table 4). Even at a relatively modest daily average cumulative feed burden of 9.6 g feed per cubic meter of water flow, the measured oxygen demand across the tank was 7.4 mg/L, i.e., the difference in inlet and outlet DO. Assuming quasi-steady state conditions, a mass balance estimates that 0.8 kg of oxygen would have to be consumed by fish (and BOD in the water) for every kilogram of feed consumed to account for 7.4 mg/L of daily average oxygen each pass across the culture tank. The CO_2 limits for smolts have not been established for salmon in RAS; however, when exposing large salmon reared in high alkalinity RAS, there was no adverse effects of 20 mg/L CO_2 when compared to 10 mg/L (Davidson et al., 2011a; Good et al., 2018). Hence, the recirculating system was maintaining relatively safe dissolved oxygen and CO_2 concentration in the outlet of Tank 1. However, in low alkalinity water, in flow-through mode (not RAS), Fivelstad et al. (2015) reported that Atlantic salmon smolt reared in freshwater is unchanged at CO_2 concentrations up to 15 mg/L, but that minor reductions in growth occur between 15 and 20 mg/L. These authors caution that at higher CO_2 concentrations, reductions in growth increase more rapidly. In addition, TAN concentration measured in samples collected at the outlet of Tanks 1 and 2 averaged 0.88 ± 0.01 and 2.19 ± 0.06 mg/L. Nitrite nitrogen concentrations were also lower at the outlet of Tank 1 than at the outlet of Tank 2, i.e., 0.26 ± 0.01 mg/L versus 0.79 ± 0.56 mg/L, respectively (Table 4). The differences in TAN and NO_2-N concentration at the outlet of each tank suggests differences in biofilter performance in the different RAS.

3.1.2. Tank 2 (653 m^3 in size)

Tank 2 of size 643 m^3 has a radius of 8 m, which allowed the measurement of water velocity at seven discrete locations along one side of the tank's radial axis and at three different depths (Fig. 5). Corresponding magnitude velocity fields are shown for the tank when operated with fish (Fig. 6a) and without fish (Fig. 6b). The velocities in both cases are observed to decrease from the wall to an intermediate radial location (~4m) and then increase to maximum value at a radial location of about 1.5–2 m from the tank centre. The maximum velocity was substantially higher without fish present (i.e., ~47 cm/s), than with fish present (i.e., ~34 cm/s). The lowest velocity was registered near the tank centre, i.e., at 0.15 m radius and approximately above the fish exclusion screen covering the centre drain. The decrease in velocity near the centre was more abrupt with fish present. In addition, the tank with fish had a more uniform velocity profile than the tank without fish. Also of note, the velocities in the larger tank with a HRT of 42 min were similar in magnitude with the velocities measured in Tank 1 when fish were present, but it was operated with a much more rapid HRT of about 22 min.

Maximum cumulative feed burden on Tank 2–with a mean HRT of 42 min − was approximately 17 g feed/m^3 of water flow on a daily

Table 3
Summary of measured water quality parameters and used probes/methods.

Parameter	Instrument/method	Location
Flowrate	Portaflow 300 Flowmeter, Micronics Ltd, UK	Inlet pipes
Velocity	Acoustic Doppler Velocimetry, Nortek AS, Norway	At definite points across the central vertical plane
Dissolved Oxygen	DO Handy Polaris, OxyGuard, Denmark	At definite points across the central vertical plane
Dissolved Oxygen	DO Handy Polaris, OxyGuard, Denmark	Inlet & Outlet
CO_2	Dissolved CO_2 sensor, Franatech, Germany	
Conductivity & pH	pH-electrode Sentix 980, WTW, Germany	
TSS	Method 2540 D (TSS dried at 103 −105 °C)	
Alkalinity	Method 8203, Digital titrator, Hach, USA	
NO_2−N/NO_3−N/TAN	Method 350.1, Automated analyzer, Flow Solution IV,OI Analytical, College Station, TX, USA	

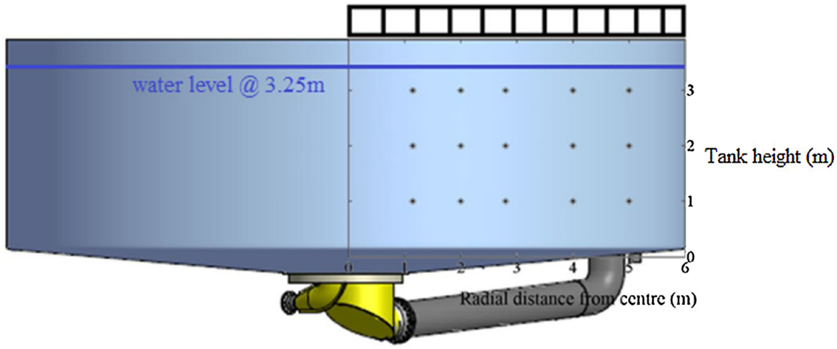


Fig. 3. Measurement points on the central radial plane for Tank 1 (368m^3) at Site 1.

average. The oxygen, CO_2, and TSS concentrations measured at the tank outlet were 8.6 ± 0.2 mg/L, 18.6 ± 1.0 mg/L, and 12.1 ± 4.0 mg/L, respectively (Table 4). The maximum cumulative feed burden on the culture tank was estimated to produce an oxygen demand of approximately 10.4 mg/L each pass. Assuming quasi-steady state conditions, a mass balance estimates approximately 0.61 kg of oxygen was consumed by fish for every kilogram of feed consumed. Although dissolved oxygen levels exiting the tank are considered safe, the CO_2 concentration were at the high end of recommended safe levels, as mentioned above.

3.2. Site 2: Octagonal tanks in North-Western Norway

3.2.1. Effect of biomass on flow velocity: case of tank 1

Although average velocity is the parameter used to calculate impulse force, distribution of velocity throughout the culture tank is important because a considerable gradient can arise radially, between the tank centre and walls. This velocity gradient plays a vital role in the distribution of water quality parameters and therefore the fish behaviour. Fig. 7 shows the measurement points across the vertical plane near the centre of the tank, where the velocimeter and DO probe were temporarily placed to obtain the parameter readings. These 14 × 3 points were used to resolve the planar distributions.

The resulting planar velocity fields for a given set of operating conditions are depicted in Fig. 8a and b for the Tank 1 without fish and with fish, respectively. When the tank was operated with biomass, the lowest velocity of about 20 cm/s was observed near the tank walls, while twice this velocity was registered at a radial distance of 2 m from centre. The sucking action of the vertical outlet pipes near the tank's bottom surface pulls on the water flow, which results in increased velocities in this location. Such a flow pattern indicates more mixing and higher velocity near the central outlet system. The steady increase in the velocity magnitude from the walls to the centre is expected to increase at higher flow rates, as higher flowrates could be used to reduce tank HRT. Interestingly, when the tank was operated without biomass, the highest and lowest water rotational velocities were measured at the tank perimeter (near the wall) and the tank centre respectively, which is opposite to the velocity profile when biomass was present. Similar trend was observed across the Tank 2 with reduced momentum concentrations, which is due to lower flow rate (Fig. 9).

Table 4
Water quality measurements (mean ± standard deviation) at the inlet and outlet of smaller tank and larger tank at Site 1.

	Tank 1 (368 m^3 size)		Tank 2 (653 m^3 size)	
	Inlet	Outlet	Inlet	Outlet
O_2 (mg/L)	16.5 ± 1.3	9.1 ± 0.3	19.0 ± 1.7	8.6 ± 0.2
CO_2 (mg/L)	8.0 ± 1.8	16.4 ± 1.4	13.1 ± 1.6	18.6 ± 1.0
Conductivity	5.1 ± 0	5.1 ± 0	17.3 ± 0	17.3 ± 0
pH	7.16 ± 0.03	6.87 ± 0.04	7.33 ± 0.04	7.13 ± 0.02
TSS (mg/L)	9.9 ± 0.2	10.0 ± 0.4	9.8 ± 1.5	12.1 ± 4.0
Alkalinity (mg/L)	71 ± 19	81 ± 5	197 ± 5	205 ± 2
NO_2-N(mg/L)	0.26 ± 0	0.26 ± 0.01	1.0 ± 0.11	0.79 ± 0.56
NO_3-N(mg/L)	15 ± 2	17 ± 0	41 ± 1	42 ± 1
TAN (mg/L)	0.61 ± 0.04	0.88 ± 0.01	1.67 ± 0.15	2.19 ± 0.06

3.2.2. Effect of fish density on oxygen distribution: case of tanks 1 and 2

DO concentration ranged from approximately 8.6–10.0 mg/L across the measurement plane (Fig. 10), corresponding to saturation levels ranging from approximately 78% to 92% (Table 5). Higher oxygen concentrations at the outer radii are likely due to the incoming flow and fish distribution. Lower oxygen levels registered at the centre of the tank, i.e., where practically 100% of the flow exits at the bottom, indicate the need for improved mixing across the tank. These findings are

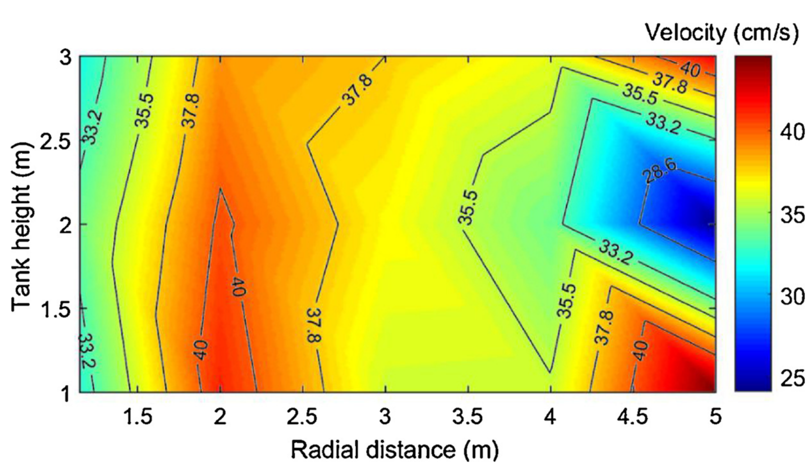


Fig. 4. Velocity contours across the measurement plane for Tank 1 (368m^3 size) at Site 1.

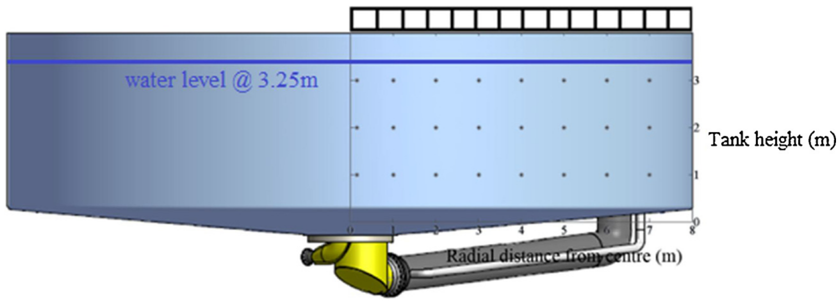


Fig. 5. Measurement points on the central plane Tank 2 (653m^3) at Site 1.

consistent with the observations made in an earlier sampling (unpublished) at the same facility but with slightly different biomass. Ideally, dissolved oxygen concentration should never be allowed to drop below 85% of saturation anywhere in the culture tank (Thorarensen and Farrell, 2011). Additional dissolved oxygen probes could be located at various places in the tank volume, thereby giving a much more detailed picture of DO distribution than is common today. Using a programmable logic controller in a feedback control loop to automatically adjust the amount of oxygen feed gas added up-stream of the culture tank, such a multiple sensor set-up could act to maintain the dissolved oxygen profile at the bottom-centre of the tank at more ideal levels.

3.2.3. Water quality measurements

In tanks 1 and 3 at Site 2, fish were taken off feed on the sampling day in preparation for transfer to sea. The maximum cumulative feed burden on tanks 2 and 4 at Site 2 on the day of sampling were approximately 28 and 26 g feed per m^3 flow on a daily average, respectively. The cumulative feed burden across the fed tanks at Site 2 was approximately 3-times greater than that estimated across the tanks at Site 1 (Table 2) because the fed tanks at Site 2 were operated at a relatively high feed rate and a higher mean tank HRT than the tanks at Site 1. The oxygen, CO_2, and TSS concentrations measured at the outlet of fed tanks 2 and 4 were: 8.6 ± 0.1 and 9.1 ± 0.3 mg/L, 16.4 ± 1.4 and 22.8 ± 0.8 mg/L, and 5.1 ± 1.5 and 3.0 ± 0.2 mg/L,

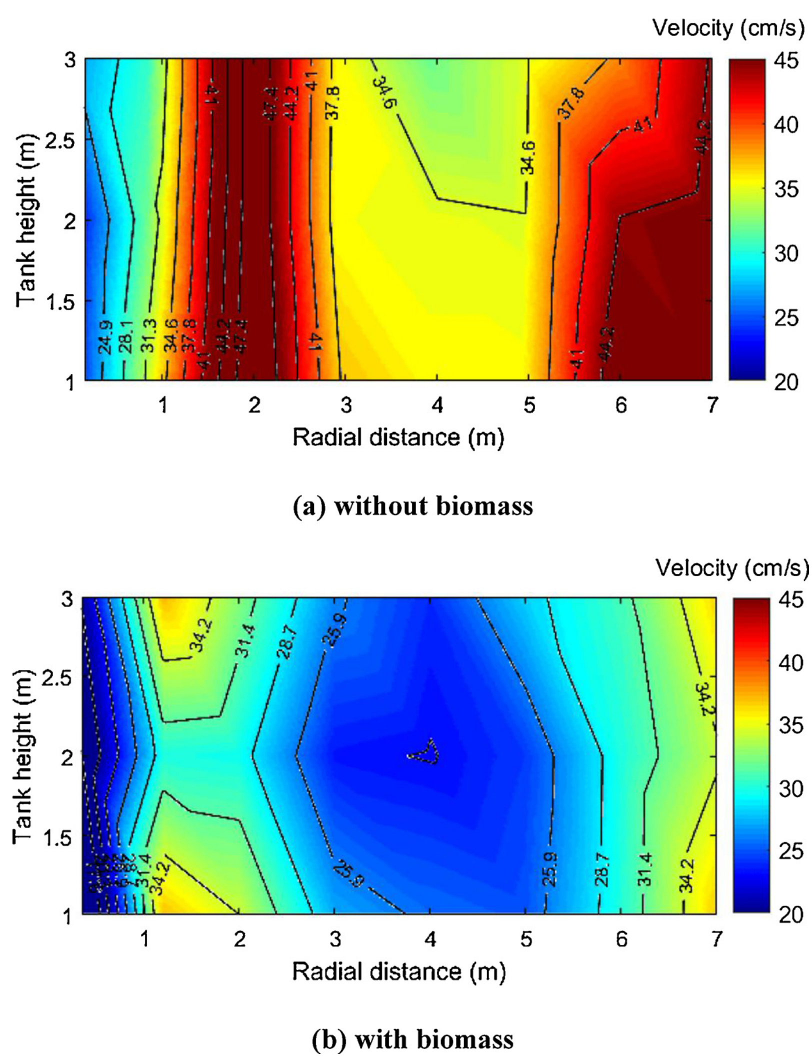


Fig. 6. Velocity map showing the influence of biomass on the flow pattern of circular RAS tank of 653m^3 size at Site 1.

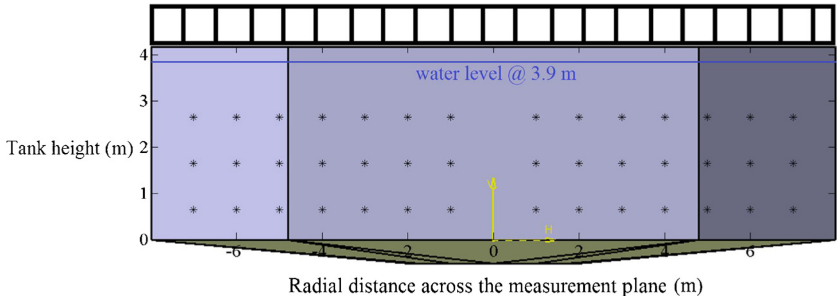


Fig. 7. Measurement points for the tanks at Site 2 across the radial plane at every 1 m in horizontal and vertical directions.

respectively (Table 5). The water treatment processes in the recirculating system and the culture tank hydraulics combined to control dissolved oxygen, carbon dioxide, and TSS that would be considered close to optimum in Tanks 2 and 4, except for the elevated CO_2 at the outlet of tank 2, particularly when considering the relatively high cumulative feed burden applied. Measured oxygen demand across fed tanks 2 and 4 were 9.2 and 7.4 mg/L (i.e., inlet – outlet concentrations; Table 5). Measured oxygen demand across unfed tanks 1 and 3 were 4.6 and 3.6, respectively. The lower oxygen demand across unfed tanks is as expected with tank exchange rate near equal for fed and unfed tanks. Assuming quasi-steady state conditions, a mass balance estimates approximately 0.33 and 0.29 kg of oxygen was consumed by fish for every kilogram of feed consumed across fed tanks 2 and 4, respectively. We note that the relatively low oxygen consumption by the fish in the fed tanks corresponds to a culture environment with relatively low TSS levels, e.g., about 3–5 mg/L. In addition, mean TAN and NO_2-N concentrations in the outlet of the fed culture tanks ranged from 1.9 to 2.2 mg/L and from 1.2 to 1.9 mg/L, respectively. In contrast, mean TAN and NO_2-N concentrations in the outlet of unfed culture tanks (but with fish) only ranged from 0.36 to 0.70 mg/L or were 0.1 mg/L, respectively. Although these mean NO_2-N concentrations would normally be considered high in terms of fish health; they are not considered high if chloride is added to minimize toxicity (Wedemeyer, 1996).

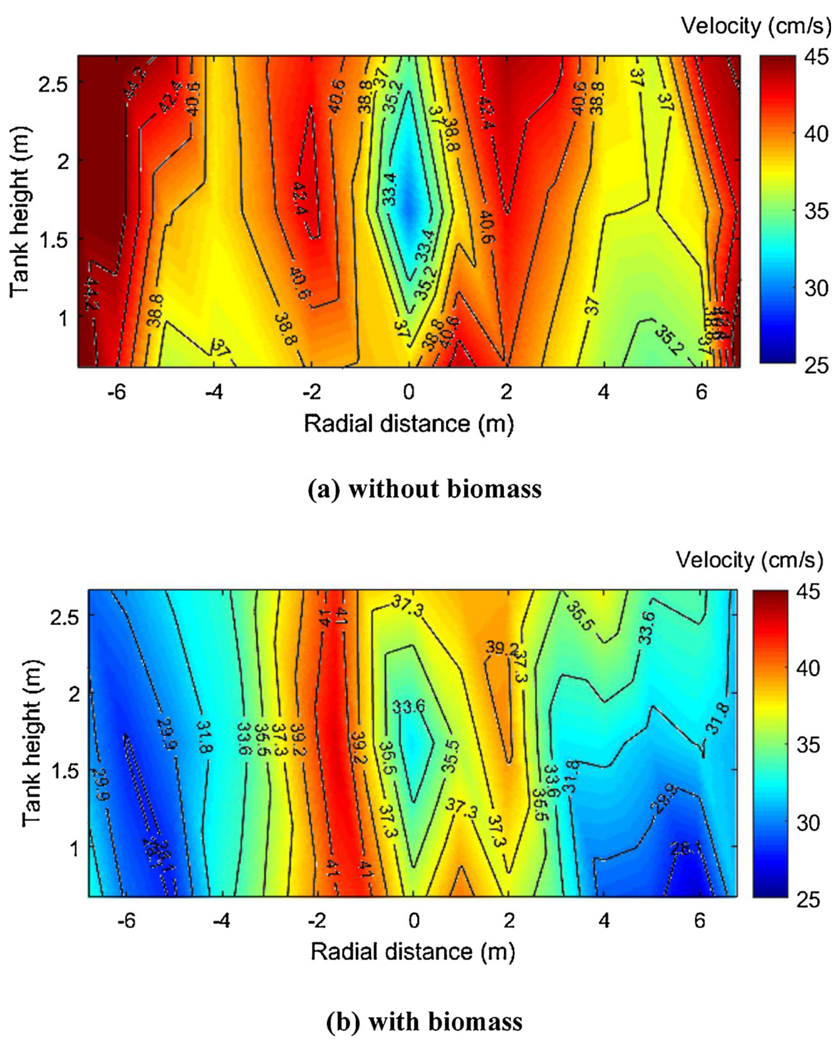


Fig. 8. Effect of biomass on the velocity distribution in octagonal Tank 1 at Site 2. Flow rate in both cases is 15.8 m^3/min, which corresponds to a mean HRT of 45 min. Biomass density in (b) is 53.9 kg/m^3.

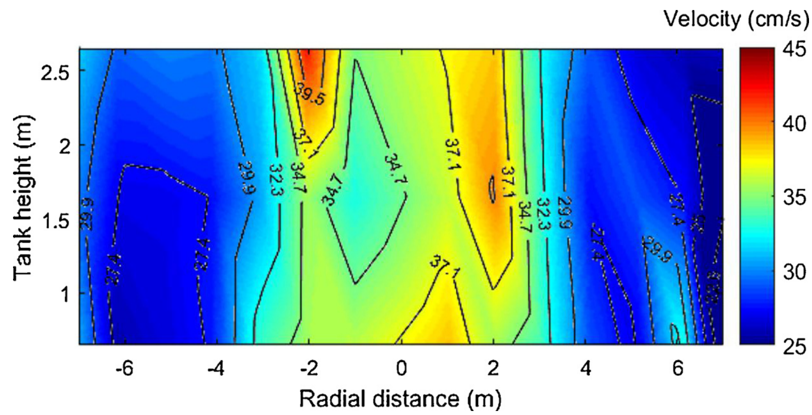
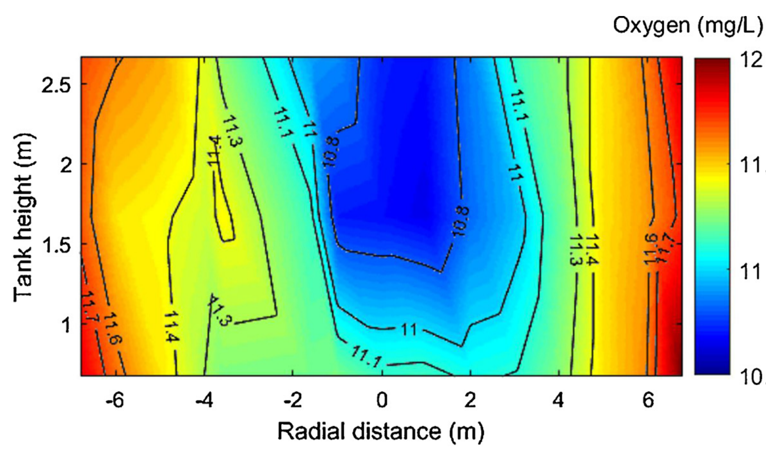


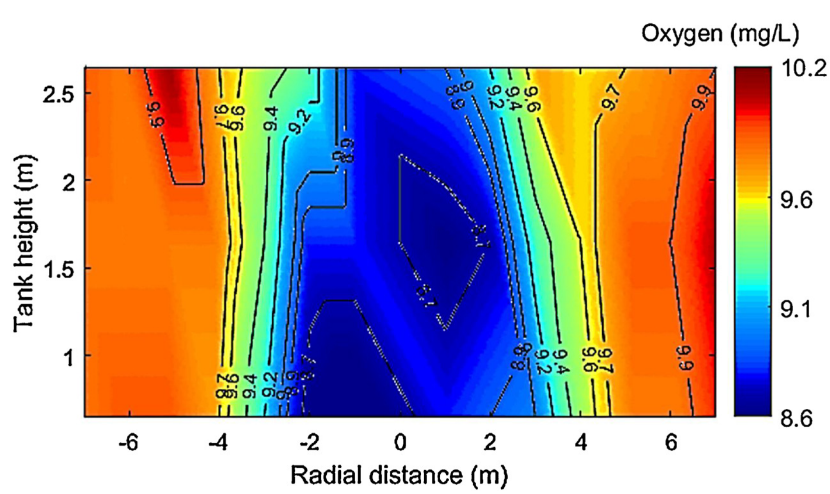
Fig. 9. Velocity profile of Tank 2 at Site 2 with a biomass density of 74.2 kg/m^3. Flowrate is 12.3 m^3/min, which corresponds to a mean HRT of 64 min.

4. Discussion

An empirical study to characterize water rotational velocity and water quality was completed in three large culture tanks at two commercial salmon smolt and post-smolt sites. The results suggest that the water rotational velocities recorded in all three tanks sampled were sufficient to maintain self-cleaning conditions and were close to optimum swimming speeds recommend for Atlantic salmon, even with



(a) Tank 1 (Flow rate = 15.8 m^3/min, biomass density = 53.9 kg/m^3)



(b) Tank 2 (Flow rate = 12.3 m^3/min, biomass density = 74.2 kg/m^3)

Fig. 10. Dissolved oxygen distribution in the tanks at Site 2 with different operating conditions.

Table 5
Water quality (mean ± standard deviation) measured at the inlet and outlet of the tanks at Site 2.

	Tank 1		Tank 2		Tank 3		Tank 4	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
O_2 (mg/L)	16.5 ± 0.3	11.9 ± 0.2	17.8 ± 1.0	8.6 ± 0.1	14.3 ± 0.4	10.7 ± 0.1	16.5 ± 1.3	9.1 ± 0.3
CO_2 (mg/L)	4.2 ± 0.2	10.6 ± 0.3	10.6 ± 0.9	22.8 ± 0.8	3.8 ± 0.0	10.7 ± 1.0	8 ± 1.8	16.4 ± 1.4
Conductivity	19.8 ± 0.0	19.8 ± 0.0	10.1 ± 0.5	10.3 ± 0.1	20.4 ± 0.0	20.4 ± 0.0	5.1 ± 0.0	5.1 ± 0.0
pH	7.4 ± 0.0	7.1 ± 0.0	7.2 ± 0.1	6.8 ± 0.1	7.4 ± 0.0	6.9 ± 0.0	7.2 ± 0.0	6.9 ± 0.0
TSS (mg/L)	6.5 ± 2.7	8.3 ± 1.6	2.1 ± 0.5	3.0 ± 0.2	3.5 ± 0.1	5.7 ± 0.1	2.3 ± 0.4	5.1 ± 1.5
Alkalinity (mg/L)	56 ± 6	75 ± 2	74 ± 6	83 ± 6	51 ± 6	52 ± 4	63 ± 1	71 ± 4
NO_2—N (mg/L)	0.1 ± 0	0.1 ± 0	1.6 ± 0.7	1.9 ± 0.8	0.1 ± 0	0.1 ± 0	1.1 ± 0.0	1.2 ± 0.1
NO_3—N (mg/L)	6.6 ± 1	7.7 ± 0.2	16.4 ± 0.2	16.6 ± 0.4	4.9 ± 1.3	5.0 ± 0.7	23.7 ± 0.1	23.8 ± 0.2
TAN (mg/L)	0.3 ± 0.1	0.7 ± 0	1.7 ± 0.3	1.9 ± 0.2	0.28 ± 0.1	0.36 ± 0	1.9 ± 0.1	2.2 ± 0.0

substantial differences in tank HRT, volumes, and drain structures and locations.

4.1. Water rotation without fish

All three tanks incorporated two vertical flow inlet pipes that distributed inlet flow through orifices. All vertical inlet pipes were located adjacent to the wall of each culture tank. Both circular and octagonal tanks exhibited a relatively uniform velocity field in the vertical water column at each radial location, when sampled with no fish (Figs. 6a and 8a). The highest rotational velocities are recorded near the walls, which is, as expected, due to predominant tangential flow injected from inlet pipes near the walls. Also, there are peak velocities at intermediate radial locations nearly at 2 m from the centre of the tanks, which is possibly due to the central bottom drain in both configurations of tanks. Such an outlet system likely creates cylindrical vortex extending from the water surface down to the tank's bottom. The wavy nature of maximum velocity at the water surface in case of Tank 2 at Site 1 diffuses at the tank's bottom. This trait is not observed in the circular tank at Site 1. Water column has thus little influence on the vertical velocity gradient in large circular tanks. The exact reason why the vertical zones of relatively high and low water rotational velocity zones were at different locations in the octagonal tank compared to the circular tank is uncertain. However, we hypothesize that the different locations for water withdrawal may contribute to these different velocity profiles. All of the flow is withdrawn at the bottom-centre drain in the tanks at Site 2, but approximately 80% of flow is drained through the bottom-centre in the two tanks at Site 1 (leaving 20% of the flow exiting through the sidewall drains). Another key observation is concerned about the velocity gradients in radial direction in both the tanks. This indicates that the tank shape in addition to its size plays an important role in developing the velocity field along the radius in culture tanks.

The magnitude of water rotational velocities recorded in the large circular and octagonal tanks with fish were surprisingly similar even with large differences in tank HRT and tank volumes (Table 6). The circular tanks at Site 1 operated at HRTs of 22 min (Tank 1) and 42 min (Tank 2), considerably more rapid flushing rates than the 64 min HRT encountered in the 788 m^3 tank at Site 2. In addition, minimum (25–26 cm/s) and maximum water (40 cm/s) rotational velocities were almost identical in the largest and smallest culture tanks, i.e., 788 m^3 versus 368 m^3. These tanks also had the greatest difference in HRT's, i.e., 64 min versus 22 min, respectively. This suggests that in each distinct application, the culture tank designers and facility operators had sufficient experience to optimized flow inlet nozzle velocity and orientation to achieve appropriate tank rotational velocities over a gamut of conditions, including large variations in tank size, HRT, and outlet structures.

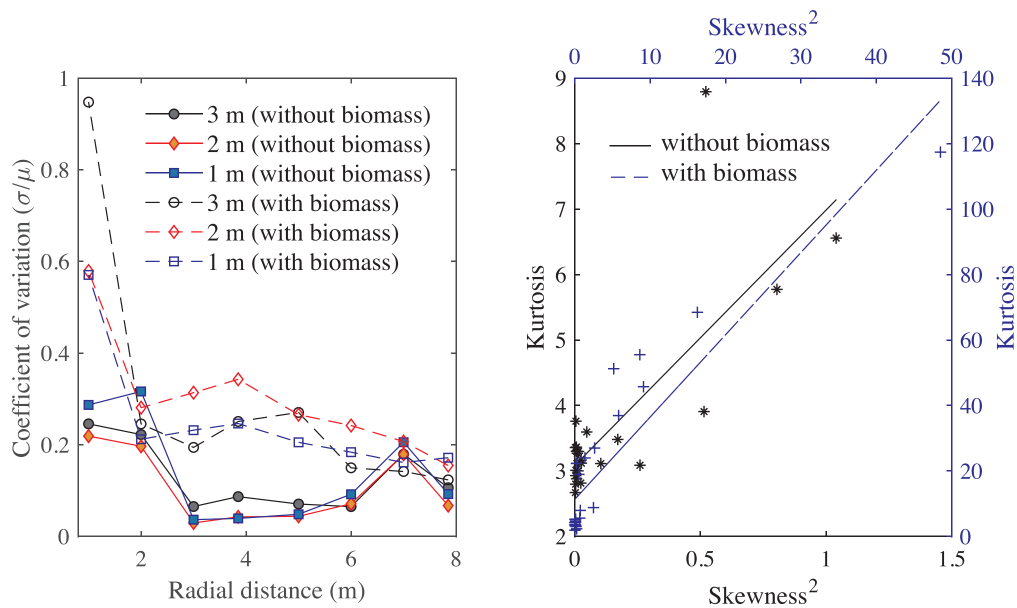
Table 6
Tank volume, HRT, approximately fish length, measured rotational velocity, and estimated swim speed in the three tanks at sampling.

	Tank volume (m3)	Tank HRT (min)	Approx. fish length (cm)	Measured velocity (cm/s)	Estimated swim speed (BL/s)
Site 1	653	42	23	17–34	0.7–1.5
Site 1	368	22	22	26–40	1.2–1.8
Site 2	788	64	27	25–40	0.9–1.5

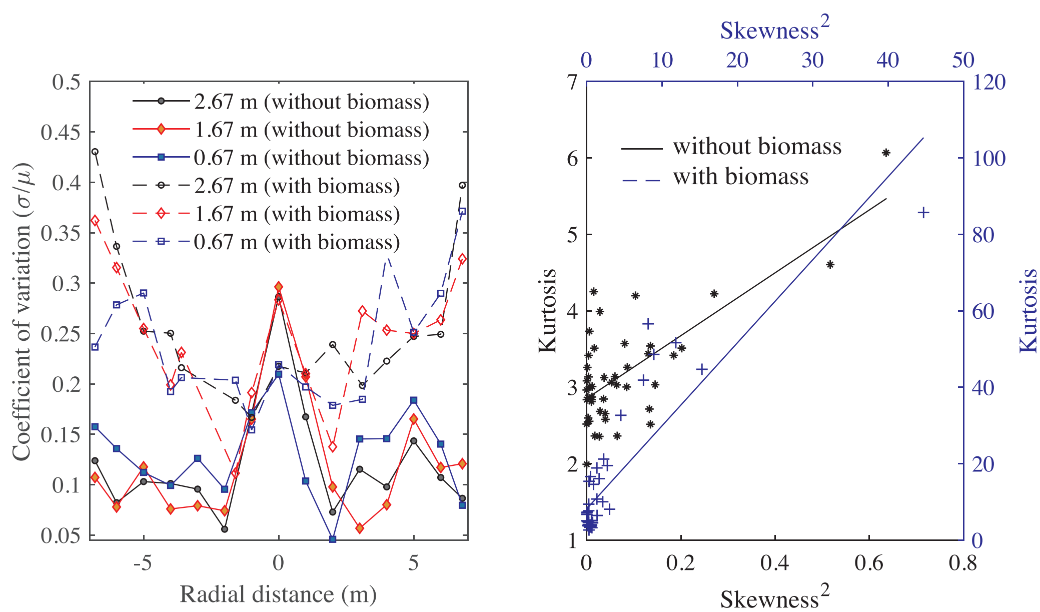
4.2. Water rotation with fish

There is a considerable impact of fish swimming on the flow domain of culture tanks. It is associated with the natural dynamics of fish motion, which is more critical in land-based systems, because the school of fish creates as well as experiences non-linear fluid dynamics and time-dependent turbulent features. Referring to Figs. 6b and 8b, which explain the velocity contours in the larger circular and octagonal tanks respectively, the velocity magnitude is lower near the tank walls than at a radial distance of 2 m from the centre, which is in contrast to that in empty tank. This is usual, because fish tend to occupy the region with higher oxygen, which is near the wall due to the inlet. The highest water rotational velocities in the tanks sampled at Site 2 tended to be located within a radial distance of 3 m of the tank centre; water rotational velocities at locations closer to the tank perimeter were almost half the speed closer to the tank centre. In contrast, both tanks sampled at the Site 1 tended to produce relatively higher water velocities at two distinct radial locations, i.e., adjacent to the tank wall and then again at a radial location between approximately 1–3 m from the tank centre. In the tanks at Site 1, relatively slower velocities were produced at both the centre of the tank, i.e., just about above the flow outlet screen, and again approximate to the radial location mid-tank. The linear variation in the velocity magnitude in radial direction, however at different scale, was retained at a larger portion of the tanks with fish. One major discrepancy occurred and this was at a location near the wall of the 383 m^3 tank (Fig. 4). Additionally, the water rotational velocity samples could only be collected at locations adjacent to the overhead access platforms, which confounds a direct comparison between the velocity profiles measured in the tanks. Thus, spacing was inconsistent between the tanks with respect to the distance between the nearest flow inlet pipe that is "up-current" and the location of the vertical plane that was sampled for flow velocity.

Flow blockage created by the biomass is a major contributor to the reduced rotational velocity in the tank. Using empirical studies in a 737 m^3 circular culture tank without fish or with fish at three densities, Plew et al. (2015) determined that increasing fish density reduced water velocities, altered the spatial distributions of velocities, and increased turbulence. Mean water velocity, reported by Plew et al. (2015), was reduced to approximately 20 cm/s with fish present, which is approximately 1/3-less than the 30 cm/s average velocity reported in the same tank when operated without fish. Similarly, the present study suggests a 25% drop in the velocity due to the presence of fish biomass. However, the trends of mean velocity in the radial direction remain



(a) Circular tank - 2 at Site 1



(b) Octagonal tank - 1 at Site 2

Fig. 11. Statistical moments of velocity measurements. Coefficient of variation is significant with fish present in the tank (left), and corresponding measurement data likely has heavier tails due to higher kurtosis than the that with no fish in the tank (right). Skewness is the measure of asymmetry in the statistical distribution and higher kurtosis represents more outliers.

unchanged, which allows the fish to select a variety of water velocities. This observation is consistent with Timmons et al. (1998).

Another influence of fish on the quality of measurement data is that they create more fluctuations in the velocity magnitude due to the turbulence created by their motion. This resulted in increased deviations from the mean velocity. Because the measurements were conducted in different tanks with different biomass properties under different flow conditions, the coefficient of variation (COV) was considered as a better representor to quantify and compare the data variability. The plots of COV in Fig. 11 for circular and octagonal tanks reveal that the data collected near the water surface is more dispersed than at depths. Draining flow in the circular tank at the centre displayed the highest variability in the order of the magnitude of flow velocity near the water surface. Dynamics of sinking vortex at this location was the major contributor to the data deviation from the mean value. On the other hand, though the water was collected at the centre in case of the octagonal tank, it was made to flow through the vertical pipes in to the casing at the top, where it gets out of the tank. While eliminating the central bottom drain, this design also avoids the presence of strong sinking vortex in the culture tank. The result is therefore a reduced COV of about 60%. The fish in the tank has increased the average slope of COV plots by twice in circular tank, while it is 4 times in the octagonal tanks. These observations are complemented by the Skewness-Kurtosis plots, where the overall kurtosis with fish is over 5 times higher than that without fish. A positive skewness of the data implies the tendency to have higher velocities than the mean. The scatter plot of unscaled skewness and kurtosis gives the information about the distribution of time-depended randomness in the velocity magnitude. While a non-zero skewness, which is due to flow turbulence, is the most common observation, negligible temporal asymmetry characterised by zero-skewness is evidenced with certain data points. Velocity distributions with skewness close to zero but with a higher kurtosis indicate peaky signals, which tend to attain higher probability of extreme events such as intensive turbulence. On a whole, the empirical data collected from the tanks without fish is closely following g-and-h distribution with $h > 0$, while that with fish likely falls within g-and-h distribution with $h < 0$.

4.3. Oxygen respiration, water velocities, and TSS

Minimum and maximum water velocities measured in the vertical cross-sections of the three tanks ranged from 17 to 26 cm/s and 34–40 cm/s, respectively (Table 6). Atlantic salmon mean length ranged from approximately 22–27 cm in these tanks at the time of sampling. Thus, simply to maintain their position at different locations in this velocity field would have required that these fish swim at a minimum of 0.7–1.2 body lengths per second and a maximum of 1.5–1.8 body lengths per second. The ideal swimming speed for Atlantic salmon of this size is approximately 1–1.5 body lengths per second, which has been shown to improve growth rate, disease resistance, and is associated with modulation of several genes important for robustness (e.g. Davison, 1997; Castro et al., 2011; Ytrestøyl et al., 2013). In the present study, all three culture tanks then provided near ideal water velocities for swimming salmon to hold position in the flow.

Swimming speed also impacts oxygen consumption in Atlantic salmon (Forsberg 1994; Castro et al., 2011). Data collected on DO and flow rates during the present study allowed estimates of the mass of oxygen consumed by fish for every unit mass of feed consumed in the three tanks. However, large variation in these estimates, which ranged from approximately 0.3–0.8 kg of oxygen consumed per kilogram of feed fed (Table 7), suggests that more research is necessary to identify if these are real deviations or empirical errors. If these deviations are real, they may be produced by: (i) increased oxygen respiration exerted by higher levels of biosolids and TSS in the water and not by the fish; (ii) increased oxygen respiration exerted by Atlantic salmon when exposed to 10–12 mg/L of TSS compared to oxygen respiration at similar water velocities but with only 3–5 mg/L of TSS; or (iii) salmon swimming speeds that are actually greater than the water current in such systems. In this last case, using water rotational velocity as a proxy for swimming speed may not be reliable when estimating oxygen respiration. It would be a significant finding, if the estimated oxygen respiration rate does actually double from 0.29–0.33 kg O_2/kg feed to 0.61–0.80 kg O_2/kg feed as the TSS concentration measured in the tank increases from 3 to 5 mg/L up to 10–12 mg/L, respectively. This is important from a design and operations standpoint, because doubling the oxygen respiration rate will require adding twice as much oxygen to meet the oxygen demand of the fish at the same feed load; it could also produce approximately twice the CO_2 in the same pass through the culture tank, i.e., degrading water quality. If so, these findings would provide a strong incentive to improve suspended solids control, because improving TSS control would more efficiently meet the oxygen requirements of the fish and reduce CO_2 accumulation. Note that we did not determine if the different TSS levels in culture tanks were due to differences in particle properties (e.g., size and density; as reviewed by Veerapen et al., 2005) of the fish faecal matter produced in the different tanks or due to differences in biosolids capture efficiencies of the water treatment processes in the different RAS or a combination of both factors.

4.4. Water quality, cumulative feed burden, and mean tank HRT

Estimates of the cumulative feed burden dropped dramatically with decreasing mean tank HRT, from a high of 28 g/m^3 of flow at a 64 min HRT, down to just 9.4 g/m^3 of flow at a 22 min HRT (Table 7). Based on water quality measured in tanks at both sites, the dissolved oxygen, carbon dioxide, and TSS would be considered close to optimum, except for an elevated CO_2 at the outlet of one tank, particularly when considering the relatively high cumulative feed burden applied. Thus, the water treatment processes in the recirculating system and the culture tank hydraulics combined to provide relatively safe water quality for producing Atlantic salmon smolt and post-smolt.

5. Conclusions

Large culture tanks are known for flow turbulence, non-linearities, and non-uniform conditions. Many measurements are required to characterize the flow pattern completely in such flow domains, but imposed constraints on the measuring resources, time and budget limit the experimental capacity onsite. Velocity measurements at discrete points across the central vertical plane of large commercial RAS tanks, both circular and octagonal in shape, are reported in this paper, which highlight that the biomass properties are quite significant in the velocity distribution. In addition, the effect of fish density in the tanks i.e. 35 and 48 kg/m^3 in the two circular tanks at Site 1, and 54, 74, 58 and 64 kg/m^3 in four octagonal tanks at Site 2, respectively, on the water quality was investigated, which exhibited a reasonable correlation with velocity distribution. It was also found that the water velocity was close to optimal for Atlantic salmon smolts in terms of fish performance and health, i.e. generally 1–1.5 body lengths per second. However, mere planar fields cannot provide a holistic hydraulic behaviour of such large flow domains. In order to explore the flow behaviour and manage the right hydrodynamics in such large flow domains, a comprehensive computational investigation on these facilities is underway, where the findings of this paper will be used for model validation.

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Table 7
Tank HRT and estimates of cumulative feed load, change in dissolved oxygen between tank inlet and outlet, and oxygen respiration rates, as well as measured concentration of TSS and CO_2 exiting the tank bottom drain at sampling. Data in top two rows is from Site 1 tanks and in bottom two rows is from Site 2 tanks. O_2, CO_2 and TSS measurements at tank outlet are indicated by mean ± standard deviation.

Tank HRT (min)	Cumulative feed load (g/m^3 water flow)	O_2 at tank outlet (mg/L)	O_2 Change: tank inlet – outlet (mg/L)	O_2 respiration rate estimate (kg O_2/kg feed)	TSS at tank outlet (mg/L)	CO_2 at tank outlet (mg/L)	CO_2 Change: tank inlet – outlet (mg/L)
22	9.4	9.1 ± 0.3	7.4	0.80	10.0 ± 0.4	16.4 ± 1.4	8.4
42	17	8.6 ± 0.2	10.4	0.61	12.1 ± 4.0	18.6 ± 1.0	5.5
61	26	9.1 ± 0.3	7.4	0.29	5.1 ± 1.5	16.4 ± 1.4	8.4
64	28	8.6 ± 0.1	9.2	0.33	3.0 ± 0.2	22.8 ± 0.8	12.2

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