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Survey of large circular and octagonal tanks operated at Norwegian commercial smolt and post-smolt sites

Steven T. Summerfelt[a,*], Frode Mathisen[b], Astrid Buran Holan[c], Bendik Fyhn Terjesen[c]

[a] The Conservation Fund Freshwater Institute, 1098 Turner Road, Shepherdstown, WV 25443, USA
[b] Grieg Seafood ASA, P.O. Box 234 Sentrum, 5804 Bergen, Norway
[c] Nofima, NO-6600 Sunndalsøra, Norway

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ABSTRACT

A survey was conducted to determine the geometry, operating parameters, and other key features of large circular or octagonal culture tanks used to produce Atlantic salmon smolt and post-smolt at six major Norwegian Atlantic salmon production companies. A total of 55 large tanks were reported at seven land-based hatchery locations, i.e., averaging 7.9 (range of 4–12) large tanks per land-based site. In addition, one 21,000 m^3 floating fiberglass tank in sea was reported. Culture volume ranged from 500 to 1300 m^3 for each land-based tank. Most tanks were circular, but one site used octagonal tanks. Land-based tank diameters ranged from 14.5 to 20 m diameter, whereas the floating tank was 40 m diameter. Maximum tank depths ranged from 3.5 to 4.5 m at land-based facilities, which produced diameter-to-average-depth ratios of 3.6:1 to 5.5:1 m:m. The floating tank was much deeper at 20 m, with a diameter-to-average-depth ratio of only 2.4:1 m:m. All land-based tanks had floors sloping at 4.0–6.5% toward the tank center and various pipe configurations that penetrated the culture tank water volume at tank center. These pipes and sloping floors were used to reduce labor when removing dead fish and harvesting fish.

Maximum flow ranged from 3 to 19 m^3/min per land-based tank, with 400 m^3/min at the floating tank, but tank flow was adjustable at most facilities. Land-based tanks were flushed at a mean hydraulic retention time (HRT) of 35–170 min. Maximum feed load on each land-based tank ranged from 525 to 850 kg/day, but the floating tank reached 3700 kg/day. Almost half of the large tanks reported in this survey were installed or renovated since 2013, including the three tank systems with the highest flow rate per tank (greater than 17.6 m^3/min). These more recent tanks were operated at more rapid tank HRT's, i.e., from 34.8 to 52.5 min, than the 67–170 min HRT typical of the large tanks built before 2013. In addition, flow per unit of feed load in land-based tanks that began operating before 2010 were lower (19–30 m^3 flow/kg feed) than in tanks that began operating later (33–40 m^3 flow/kg feed). In comparison, the floating tank operates at a maximum daily tank flow to feed load of 160 m^3 flow/kg feed, which is the least intensive of all tanks surveyed. Survey results suggest that the recently built tanks have been designed to operate at a reduced metabolic loading per unit of flow, a tendency that would improve water quality throughout the culture tank, all else equal. This trend is possible due to the ever increasing application of water recirculating systems.

1. Introduction

Larger culture tanks are being applied worldwide to reduce the capital and labor costs per ton of fish produced in both floating and land-based closed-containment systems for Atlantic salmon smolt and post-smolt production (Bergheim et al., 2009; Plew et al., 2015). Circular and octagonal culture tank geometries are often used because they offer many advantages when their circular rotation and completely (at least theoretically) mixed reactor hydrodynamics can be managed correctly (Timmons et al., 1998). For example, solids flushing can occur in only minutes in a properly managed circular tank, which allows waste feed and fresh faecal pellets that settle to be removed from the culture tank more rapidly than the tank hydraulic retention time and before they have the opportunity to break down. In addition, the water rotational velocity within circular tanks can be adjusted to provide the optimum swimming speed for the fish, as well as uniform water mixing such that fish are exposed to the same good water quality throughout

* Corresponding author.
E-mail address: s.summerfelt@freshwaterinstitute.org (S.T. Summerfelt).

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the tank. Hence, water velocity can be set according to fish length such that exercise to 1–1.5 body lengths per second can be used, a velocity that improves Atlantic salmon growth and disease resistance (Castro et al., 2011; Ytrestøyl et al., 2013). Also, rapid mixing within the circular tank which is at least partially due to the swimming action of the fish (Rasmussen et al., 2005; Plew et al., 2015) allows for high dissolved oxygen supersaturation concentrations to be added to circular tanks while only exposing fish to the mean tank concentration (Davidson and Summerfelt, 2004). Complete mixing also equally distributes dissolved waste metabolites such as carbon dioxide and ammonia; dissolved substances that are homogeneously distributed are flushed from the culture tank in direct proportion to its mean hydraulic retention time (Liao and Mayo, 1972).

The Norwegian salmon industry recognizes that there is great potential to reduce fixed and variable costs with the application of large circular-type culture tanks of capacity near 1000 m^3 for smolt and post-smolt production. Shifting production into fewer but larger culture tanks dramatically decreases the number of fish feeders, water quality monitoring equipment, flow inlet structures, flow outlet structures, and mort removal structures that must be installed and maintained, as well as reducing the overall building footprint, compared to the same production in larger numbers of small tanks. Savings in labor to feed and transfer of fish are also achieved using fewer larger tanks to achieve the same production goal. In addition, given that the permissive maximal number of fish per traditional sea cage is 200 000 in Norway (FDIR, 2004), it is efficient and adds biosecurity to be able to fill one sea cage from one land-based tank. However, industry recognizes that many hydrodynamic challenges still remain when such large circular tanks are operated, i.e., to ensure rapid solids flushing, proper water rotational velocities, and relatively uniform water mixing. Thus, more information is required to effectively optimize flow hydraulics within large and deep circular and octagonal tanks.

Therefore, to characterize the current status of large culture tanks in the Atlantic salmon farming industry, several companies were surveyed to identify the availability of circular tanks larger than 400 m^3 and characterize their existing operational parameters. This survey is the first part in a large research program, to be followed by measurements of water rotational velocities and tank mixing data in several of the tanks identified in this first part. In a final part, the project will develop a computational fluid dynamics (CFD) model of a near 1000 m^3 tank operated under base-line conditions, as suggested by this survey, and then verify that the model is calibrated by comparison with empirical data collected from such a tank. Once calibrated, the CFD model will be used to determine how variables such as splitting of flow to the upper and lower dual-drains, inlet nozzle velocities, and the culture tank hydraulic retention time impact water rotational velocities and mixing in large circular tanks.

2. Materials and methods

A survey was developed using a Microsoft Excel spreadsheet to calculate volumes and hydraulic retention times (HRT's) while respondents answered the following questions:

- Company Name, Farm Name, Farm Address, Name of person completing this survey, System Name,
- Number of Large Tanks, Tank Diameter, Water Depth at Wall, Water Depth at Center, Dia:Depth, Water Volume,
- Total Flow Per Tank, Total Flow at Bottom Drain, Total Flow at Elevated Drain, If Elevated Drain used is it in center or side of tank (yes/no), Mean Tank Retention Time,
- Pipe(s) inside diameter entering tank; can a flowmeter be mounted on inlet pipe? Pipe inside diameter exiting bottom drain; can a flowmeter be mounted on bottom-drain pipe? Can a flowmeter be mounted on elevated-drain pipe?
- Does an access platform span to the center of the tank? Are cages or nets hung in the tank that would prevent the water from rotating freely?
- Will you allow project scientists to visit this system to collect data?

Fig. 1. Example of octagonal tanks (14.5 m wide × ~4 m deep) grouped together in one of the recirculating systems at the Marine Harvest Steinsvik hatchery.

Follow-up emails were used to identify:

- the year that the system became operational,
- the maximum sustained feed loading on each tank, and
- the maximum fish biomass density.

The access platform question identifies whether access to use velocity and DO probes at different radial locations can be provided.

The survey will also be used to determine whether flowrate could be measured entering the tank and exiting each drain. The question regarding the presence of an access platform will be used to identify whether access to use water velocity and DO probes at different radial locations was available.

The survey was limited to the following project industry partners in Norway: Marine Harvest, Grieg Seafood, Cermaq, Lerøy Seafood, Njord Salmon, and Bremnes Seashore.

3. Results

All of the project industry partners responded to the survey, although not every partner reported tanks larger than 400 m^3. Survey results are shown in Table 1.

The 21,000 m^3 floating fiberglass tank in sea was typically excluded from the summary below, unless specifically noted, because its scale was simply incomparable. Otherwise, all of the large tanks were built on land in Norway. Seven parr, smolt, and post-smolt culture facilities reported a total of 55 large tanks, i.e., averaging 7.9 (range of 4–12) large tanks per location.

The mean culture tank volume ranged from 500 to 1300 m^3 per tank (21,000 m^3 for the floating fiberglass tank). Tank diameters ranged from 14.5 to 20 m diameter (40 m at the floating tank); some were octagonal tanks (Fig. 1) but most were circular (Fig. 2) in design. Maximum tank depths ranged from 3.5 to 4.5 m, which produced diameter-to-average-depth ratios of 3.6:1 to 5.5:1 m:m. The floating tank was much deeper at 20 m, with a diameter-to-average-depth ratio of only 2.4:1 m:m. All tanks had sloped floors toward the tank center, with the tank center deeper than the tank wall by 0.3–0.65 m, i.e., a slope ranging from 4.0 to 6.5%. The strong

Table 1
Survey results on tank #, dimensions, flow rates and flow splits, drain locations, mean hydraulic retention time, availability of access platform, and year of start-up.

Farm Location	A	A	B	C	D	E	F	F	G	H
Number of Large Tanks	5	4	12	6	8	8	2	2	8	1
Tank Shape	Circular	Circular	Octagonal	Circular	Circular	Circular	Circular	Circular	Circular	Circular
Tank Diameter, m	20	15	14.5	16	16	14	18	16	16	40
Water Depth at Wall, m	3.85	3.8	3.9	3.8	3	3.15	3	3	3.5	14
Water Depth at Center, m	4.5	4.1	4.2	4.2	3.5	3.5	3.5	3.5	4	20
Diameter:Depth (mean depth; m:m)	4.8:1	3.8:1	3.6:1	4.0:1	4.9:1	4.2:1	5.5:1	4.9:1	4.3:1	2.4:1
Water Volume, m^3/tank	1311	698	788	804	653	512	827	653	754	21000
Total Flow Per Tank[a], m^3/min	12	9	17.6	12	18.75	3	16.67	16.67	10.4	400
Flow at Bottom Drain, m^3/min	4	7	Uncertain split	12	15	1,5–3	16.67	16.67	10.4	80
Flow at Elevated Drain, m^3/min	8	2	Uncertain split	NA	3.75	NA	NA	NA	NA	320
Flow Split to Bottom Center Drain, %	33	78	Uncertain split	100	80	100	100	100	100	20
Location of Elevated Drain	Tank Sidewall	Tank Sidewall	Tank Center	NA	Tank Sidewall	NA	NA	NA	NA	Tank Sidewall
Mean Tank Retention Time, min	109.2	77.5	44.8	67.0	34.8	170.5	49.6	39.2	72.3	52.5
Max. Sust. Feed Load, kg/d/tank	850	NA	700	525	700	145	600	NA	800	3700
Flow per unit of feed load, m^3/kg	20	NA	36	33	39	NA	40	NA	19	160
Feed per Unit Tank Flow, g/m^3	49	NA	28	31	26	NA	25	NA	53	6
Max Fish Density, kg/m^3	70	NA	46	53	70	45–50	50	NA	40–50	20
Access platform	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	no
Year System Began Operating	2000	2000	2015	2010	2013	2001	2014[b]	2014[b]	2006	2013

[a] Maximum total design flow used in a single culture tank; some systems have the ability to operate at lower flowrates, if desired.
[b] year converted to RAS and tank flow increased.

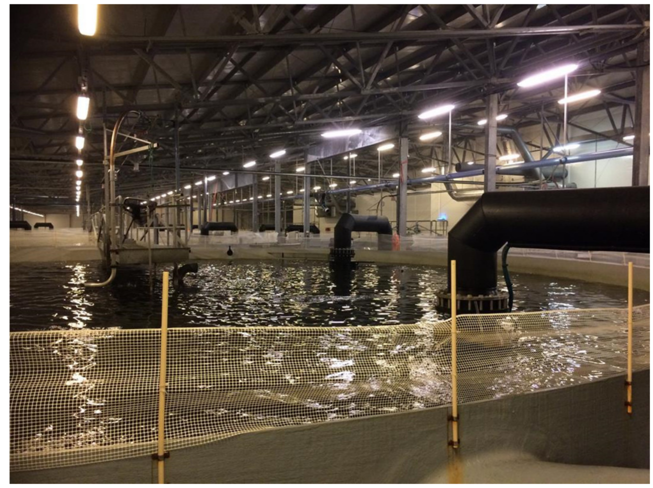

Fig. 2. Example of circular tanks (16 m diameter × 3.3 m deep) grouped together in one of the recirculating systems at the Grieg Seafood, Adamselv Culture Station.

slope to the bottom-center of the land-based tanks was a feature that allowed for pumping all fish out through a drain in the same location as water is slowly drawn out of the tank with the fish. The floating tank had a much stronger mean slope (approximately 30%) to the bottom-center drain.

Water flow through each large culture tank ranged from 3 to 19 m^3/min (400 m^3/min at the floating tank), with an adjustable flowrate reported at most facilities. The mean hydraulic retention time (HRT) at maximum reported flow ranged from 35 to 170 min. Interestingly, about half of the large tank construction or renovation projects have taken place since 2013, and the more recent tank construction/renovations are operated with much more rapid tank flushing rates, i.e., from 34.8 to 52.5 min HRT (Fig. 3). Large tanks built before 2013 were operated at much reduced tank flushing rates, i.e., from 67 to 170 min HRT.

Maximum feed load on each of the land-based tanks ranged from 525 to 850 kg/day (Table 1), but reached 3700 kg/day at the floating tank. Interestingly, feed load did not correlate with flow rate through the same tank (Fig. 4). Yet, the three tanks with the highest tank flow rate (greater than 17.6 m^3/min) were all built since 2013. Whereas, the tanks with the least flow rate (<12 m^3/min) began operating before 2011.

Maximum biomass densities ranged from 40 to 70 kg/m^3 at the land-based facilities, but were only 20 kg/m^3 at the floating tank.

Fewer than half of the tanks operated dual drains. Dual-drain tanks use either an elevated drain at tank center or sidewall (Timmons et al., 1998; Davidson and Summerfelt, 2004). In nearly all cases of those tanks surveyed here, most of the flow was discharged through the bottom-center drain of the dual-drain tank, similar to the tank reported by Plew et al. (2015). The exception was the floating tank, which operated with only 20% flow through the bottom-center drain, and the reminder through side-wall drains located almost at the bottom of the tank. The overall trend of discharging most of the flow through the bottom-center drain of the dual-drain tank is counter to the trend occurring with sidewall-type dual-drain tanks typically built for salmonids in North America (Summerfelt et al., 2006).

Many of the tanks used a flushing apparatus (Figs. 5 and 6) to move dead or moribund fish from the bottom-center of the tank to a collection area that could be readily accessed. In addition, all large tanks reported use of an overhead walkway (examples shown in Figs. 1, 2, 5 and 6) to allow access to the center of the tank. The overhead walkways can sometimes provide access to mortality collection screens, fish feeders or feed flingers, or water flow

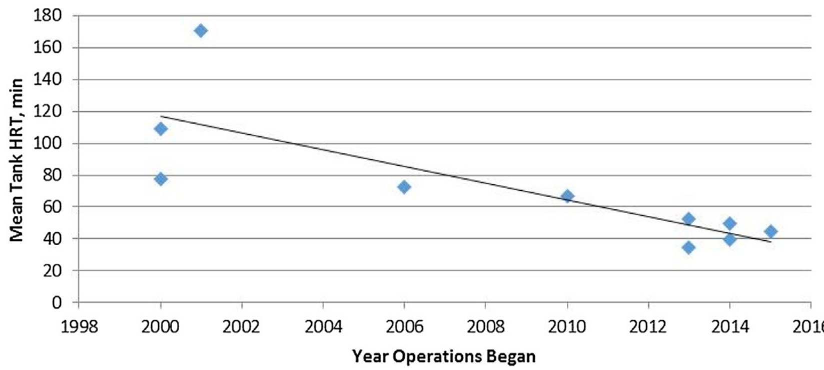

Fig. 3. Mean hydraulic retention time for large culture tanks surveyed according to the year they began operating.

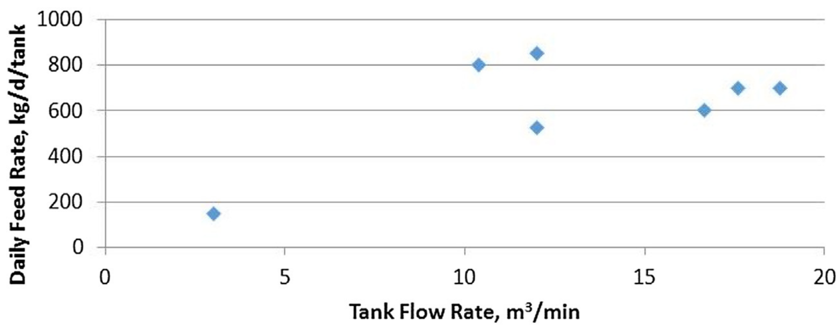

Fig. 4. Relationship between tank flow rate and the maximum daily feed rate.

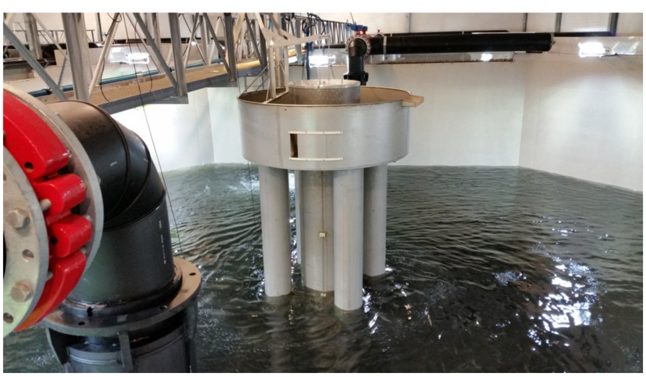

Fig. 5. A center drain and mortality collection apparatus is exposed as water and fish are pumped from a smolt tank to a central vaccination station at the Marine Harvest Steinsvik hatchery. The vertical pipes impact water rotation and mixing about the center of the tank.

inlet pipes. Installation of the mort flushing structure and overhead walkways has clearly increased the speed that dead or moribund fish can be removed from the culture tank, while at the same time use of these structures has been intended to reduce the labor required to remove dead fish. For the purpose of the 2nd phase of the project, the overhead walkways will be used to provide access to use water velocity and DO probes at different depth and radial locations across the tank.

There were no cages or nets hung in the tanks that would prevent the water from rotating freely. The culture volumes in many of these land-based tanks, however, contain vertical posts (to support overhead walkways) and/or piping (examples shown in Figs. 1, 2, 5 and 6) to flush dead fish or carry water away from the bottom-center drain. These posts and pipes create drag and reduce tank rotation and possibly negatively impact mixing, particularly close to the center of the tank. However, the mort flush apparatus and the piping used to harvest fish from the bottom of the tank are critical features that allow the large tanks to be managed with reduced labor.

4. Discussion

This large tank survey highlights the prevalence (55) of large (500–1300 m^3 per tank) land-based circular-type culture tanks (along with 1 floating tank) and a recent trend towards an increased awareness of limits on metabolic waste accumulation and general fish welfare in Norwegian land-based Atlantic salmon smolt and post-smolt facilities of the project partners. Of note, tanks installed or renovated since 2013 are operated at mean tank HRT's of 35–50 min (compared to tank HRT's of 67–171 min in the previous years) and can support higher feed loading rates and/or be used to improve flushing of waste metabolites and prevent water quality (particularly elevated dissolved CO_2) that compromises salmon performance and welfare (e.g. Thorarensen and Farrell, 2011; Terjesen et al., 2013). And as the max fish densities are not radically different along the measured timeline, the latter appears to be the case, i.e., a more rapid tank flushing rate is used to improve water quality among those tanks surveyed.

The culture tank flow per unit of feed load (Table 1) in land-based tanks that began operating before 2010 were lower (19–30 m^3/day flow per kg/day feed = 19–30 m^3 flow/kg feed), i.e., more intensely operated, than in tanks that began operating later (33–40 m^3 flow/kg feed). In comparison, the floating tank operates at a lower intensity with a maximum daily tank flow to feed load of 160 m^3 flow/kg feed; the higher flow is easy to achieve with low lift pumps with a tank floating in seawater. In land-based culture tanks that began operating before 2010, this amounts to a maximum of 33–54 g feed per cubic meter of water flushing compared to a maximum of 25–31 g feed per cubic meter of water flushing through the land-based tanks that began operating later. This metric is the maximum cumulative feed burden which is expressed in g/m3 (which is the same mg/L or ppm) of feed load per unit flow on a daily average across the culture tank. Thus, assuming approximately 20% of the feed load represents the concentration of suspended solids produced (Davidson and Summerfelt, 2005), then 5–6 mg/L of TSS would be produced on a daily average in tanks that began operating after 2010.

From a metabolic standpoint, the maximum cumulative feed burden on the culture tanks built before 2010 would consume approximately 12–21 mg/L of oxygen in a single pass across the culture tank, assuming that 0.35–0.40 kg of oxygen are consumed by swimming fish for every kilogram of feed consumed (Timmons and Ebeling, 2007). In contrast, land-based tanks built/retrofit more recently would require 8.8–12 mg/L of oxygen in a single pass across the culture tank at the maximum cumulative feed burden, all else equal. Assuming a respiratory quotient of 1 kg range 0.85–1.4 kg according to Kieffer et al. (1998) and Kutty (1968), respectively) carbon dioxide is produced for every 1 kg of dissolved oxygen consumed, this would produce approximately 8.8–12 mg/L of carbon dioxide in a single pass across the culture tank at the maximum cumulative feed burden. In conclusion, this suggests that recent tanks have been designed to operate at a lower metabolic loading per unit of flow (largely due to shorter tank HRT's in more recent tanks), which would provide improved water quality throughout the culture tank, all else being equal. This trend to operate at a lower cumulative feed burden and metabolic loading rate per unit of culture tank flow, is counter to practices reported just a decade earlier (Bergheim et al., 2009) and is now possible due to the increased use of RAS technology.

This increase in use of RAS in Norway has likely come about as a consequence of developments of the technology itself, and due to an awareness in Norway during mid 2000's that natural water bodies could not sustain future increases in smolt production, without increased water treatment and reuse (Kittelsen et al., 2006).

Land-based tanks in the survey ranged from 14.5 to 20 m diameter and were either circular or octagonal in shape, with maximum tank depths of 3.5–4.5 m. The tank design always included sloping floors and various pipe configurations that penetrate the culture tank water volume but allows for dead fish removal and fish harvest events with relatively reduced labor. However, the impact of these pipes and posts on tank hydrodynamics is yet relatively unknown. In addition to the physical presence of pipes etc., these multiple drain outlets provide more operating options. Tank operators can choose the amount of flow to draw from the bottom, side drain, or an elevated-center drain going straight into the mort box at the surface. Thus, tank hydrodynamics can be influenced either positively or negatively with the (1) added flexibility to shift the amount of water withdrawn at different tank locations and (2) inclusion of large structures that are associated with these drains (Figs. 5 and 6) that in turn increase drag and/or displace vortices in the rotating flow.

The survey results reported here are being used to choose facilities to visit in part 2 of the project, i.e., when empirical data on water rotational velocities and dissolved oxygen concentrations across a range of depths and locations along a tank cross-section are collected. The empirical data from site visits will suggest whether the rotational velocities and oxygen mixing are adequate across the culture tank, and whether inlet or outlet conditions should be adjusted. In addition, survey results will suggest tank dimensions and exchange rates that should be modelled using CFD. In the near future, work in our laboratories will begin to develop computational fluid dynamic models that can suggest how to control water rotational velocities and mixing within such large circular tanks.

Fig. 6. Large drain structures used to rapidly remove dead or moribund fish from the tank center provide a huge benefit to the tank operator but also impact culture volume hydraulics.

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