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Measurement and simulation of the three-dimensional flow pattern and particle removal efficiencies in a large floating closed sea cage with multiple inlets and drains

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ABSTRACT

This study investigated the three-dimensional flow structures in an ellipsoid, closed sea fish cage. The results are presented using computational fluid dynamics (CFD) simulations and experimental measurements. Experimental residence time distribution (RTD) measurement and CFD simulation are the best methods to study the hydrodynamics of inflow systems. Three-dimensional numerical simulations of the flow and transport characteristics of the system were conducted using a Reynolds-averaged Navier-Stokes equation approach and the results were compared to the measurements performed using acoustic Doppler velocimetry techniques. The objective of the investigation was to characterize the flow field generated in an ellipsoid, closed tank. The flow in the enclosed volume is driven by four inlets pipes integrated into the wall of the cage. The focus is on the turbulent structures and undesirable flow patterns that lead to reduced self-cleaning efficiency and a lower quality habitat for the fish through phenomena, such as recirculation zones or low velocity areas. Correlations between CFD and the experimental data confirm the adequate reproduction of hydrodynamic conditions and reinforce the predictive capabilities of numerical models as tools to simulate field scale closed containment systems or to optimize existing and future aquaculture designs. The simulation of aquaculture-like particles demonstrates that almost 100% of particles with a diameter ranging between 1 μm and 3000 μm are removed during a maximum of two hydraulic retention time (HRT) cycles. Smaller particles are removed via the upper-side outlets and larger particles are removed via the bottom outlet.

1. Introduction

The production of fish in closed containment at sea can be sustainable and are gaining more commercial interest; therefore, production efficiency measures that enable growers to control the inlet water, and thus control the water quality and the exposure to parasites, are important. This can provide efficient production with the ability to purify water for particulate material. The production of large smolt in closed facilities is thought to provide a more robust fish and allow for increased capacity in the growth phase in open systems. Lower mortality up to one kg is already found when comparing closed containment system to open net pen system (Terjesen, 2016). This new technology is driven by the need for additional measures to reduce sea lice problems in aquaculture and the possibility of increasing capacity by producing larger and more robust smolt. The Norwegian government regulations (Gullestad et al., 2011) highlights farming in land-based and closed sea-based systems in addition to expanding the ability to produce larger juveniles as well as possible measures for reducing sea lice pressure on sea trout and Norwegian wild salmon stocks. The aquaculture industry has developed several closed farming concepts for the production of fish (Chadwick et al., 2010). The development of closed sea-based systems has been accomplished in a variety of ways. One relatively quick and inexpensive approach is to use the current infrastructure and technology (float collar) and a flexible tarpaulin (bag) to create a closed rearing volume. Another option is to use a rigid or a semi-rigid tank. The shape of the defined volume will vary depending on the designs: cylindrical and ellipsoid shapes offer less drag versus the current flow velocity. All these systems will be moored in the sea using layouts similar to typical sea net pen configurations because it is assumed that many of the supporting infrastructure components would be the same. In terms of the internal hydraulics, cylindrical and ellipsoid cages in sea-based systems face problems that are similar to those faced in land-based close containment systems. The hydrodynamics within the tank is most important in terms of fish welfare due to avoidance of recirculating and low velocity zones. The self-cleaning of a fish tank, expressed as removal of the intact solid waste, minimizes

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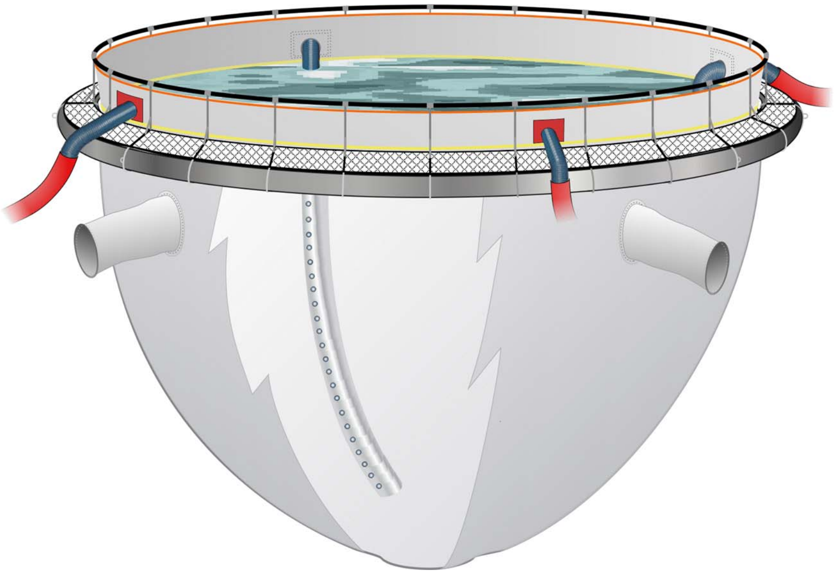

Fig. 1. Sketch of the ellipsoid, closed floating sea cage.

Table 1
Summary of the sensor locations in the rearing volume.

Sensors	Depth (m)	Distance from the center (m)
A1	3	7
A2	6	7
B	3	2
C	2.8	7

the mechanical breakdown of the particles and reduces the cost of subsequently separating the solid waste from a single effluent stream (Davidson and Summerfelt, 2005). It has recently been found that the HRT in smoltfarms have been reduces from around 120 min to around 40–50 min (Summerfelt et al., 2016). Several studies have examined tank hydrodynamics in different tank geometries (Burley and Klapsis, 1985; Cripps and Poxton, 1992), some have focused on rectangular tanks, such as raceways, which are very common in on-growing farms (Watten and Beck, 1987; Timmons and Youngs, 1991; Oca et al., 2004), and others have investigated circular tanks, which provide more uniform water quality (Rosenthal, 1987; Timmons et al., 1998; Davidson and Summerfelt, 2004; Oca and Masalo, 2007). Poor water mixing conditions can influence the welfare of the fish in a tank in several ways: changes in physiology (Odeh et al., 2003), fish exercise and behavior (Ross and Watten, 1998) and aggression and social hierarchies (Griffiths and Armstrong, 2000). The flow pattern inside the tank can also modify fish distribution, with fish showing a preference for a higher or lower velocity and for areas with different water mixing (Pavlov et al., 2000; Lupandin, 2005; Rasmussen et al., 2005; Lunger et al., 2006).

In circular tanks, the rotational velocity will create a secondary radial flow along the bottom of the tank, which will move the settled particles towards the bottom-central drain. New designs using several drains located on the side wall (known as ‘Cornell-type’ drains) have been shown to increase particle removal because they rapidly fractionate the settleable solids into the flow discharged from its bottom-center drain while discharging the majority of the relatively solid-free flow from large solid particles through elevated drains located on the side-wall. The performance of this combination of multi-drains is related to the flow split, which is the fraction of the flow through the bottom-central drain (Davidson and Summerfelt, 2004). Despres and Couturier (2004) demonstrated that very high rotational velocities in a tank should be avoided because it will lead to the creation of a strong center vortex that will result in particle resuspension.

Current knowledge is based upon studies relative small tanks compared to the commercial size that is applied in both land based and sea-based systems today. A better understanding of the flow pattern in larges units are necessary to safeguard the welfare of the fish and bring novel understanding to the field of optimising the inlet and outlet arrangements in larges aquaculture units. For example, in Norway, to

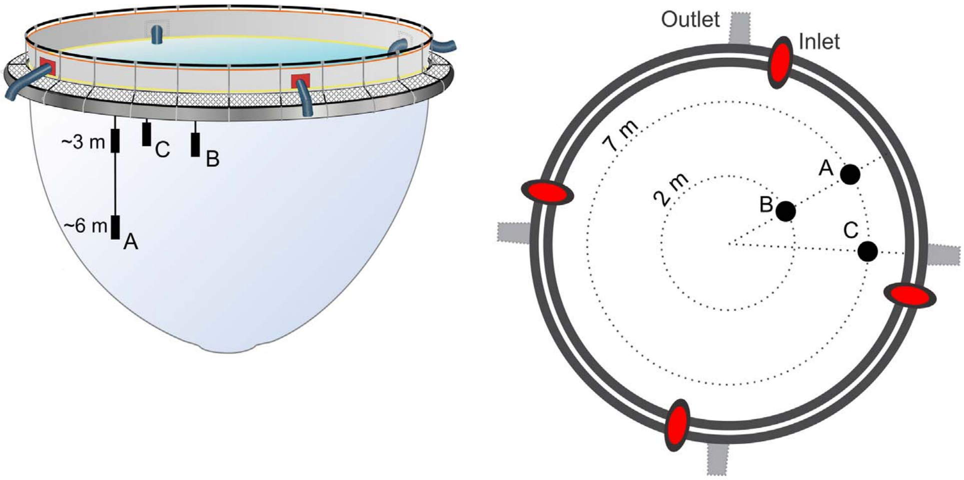

Fig. 2. Sketch on the location of the acoustic Doppler velocity sensors (ADV).