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Current flow and dissolved oxygen in a full-scale stocked fish-cage with and without lice shielding skirts

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ABSTRACT

Shielding skirts are widely used on Atlantic Salmon sea-cages as a non-invasive preventive measure against salmon lice infestations. The skirts are however known to impact the current flow and thereby the environment within the cage. As the current is influenced by local factors such as topography, farm layout and stocking density of the cage, it is difficult to compare results from sites that apply skirts with those without. The same high-stocked cage was therefore studied with and without the skirt deployed, including the transition from shielded to unshielded, to investigate the influence the skirt had on the current flow within the cage and dissolved oxygen. When the skirt was deployed the velocity vector in the centre of the cage had a vertical component towards the surface and the reduction in current speed was higher. The dissolved oxygen level inside the cage improved within 30 minutes when the skirt was removed and there was no indication of the skirt influencing the vertical swimming behaviour of the salmon.

1. Introduction

In aquaculture sea-cages a sufficient water exchange is necessary to ensure a healthy environment by supplying dissolved oxygen (DO) and removing waste and nutrient-depleted water. In 2016 the salmon lice challenges were the second highest expense for the industry in Norway (Iversen et al., 2017), and the high cost of delousing treatments (Abolofia et al., 2017; Iversen et al., 2017) has resulted in the use of preventative measures such as the non-invasive lice shielding skirts. As evidence indicates a higher lice density in the upper layers of the water column (Geitung et al., 2019; Heuch et al., 1995; Hevrøy et al., 2003; Huse and Holm, 1993; Oppedal et al., 2017), lice shielding skirts are designed to reroute this layer of the water column around the fish cage, and thereby keep the lice out by altering the current flow.

For empty cages with a shielding skirt, CFD analysis indicate that part of the ocean current is forced underneath the skirt and into the sea cage producing a recirculation pattern, where it meets the skirt in the back and is pressed up and inwards towards the centre of the cage (Lien and Høy, 2011; Lien et al., 2015). This recirculation pattern is seen in full-scale cages with skirt when the cage is empty, but not when stocked (Klebert and Su, 2020).

As the current flows through the fish cage, the current speed is reduced (Frank et al., 2015; Gansel et al., 2014; Johansson et al., 2007; Klebert and Su, 2020; Rasmussen et al., 2015; Winthereig-Rasmussen et al., 2016). The magnitude of current speed reduction as it passes through the cage is determined by the current flow pattern which is influenced by a number of factors such as farm layout (Rasmussen et al., 2015), local flow conditions at the site, local topography (Klebert et al., 2013), shielding skirts (Frank et al., 2015) and the cage structure (Klebert et al., 2015). Furthermore, reduction through plane nets increase with increasing solidity (Bi et al., 2013; Gansel et al., 2015) which can be caused by bio-fouling (Gansel et al., 2015) and increasing inclination angle between the net and the vertical plane (Bi et al., 2013). Most cages used in Norway are gravity nets, which deform as a function of the current speed (Lader et al., 2008). This deformation can alter the inclination angle and hence increase the reduction in flow velocity. The shielding skirt can also deform, and in strong currents the skirt will increasingly be pushed back and up towards the surface, resulting in potentially less obstruction for the current and lice (Lien et al., 2014).

The reduction in current speed is also influenced by the presence of fish (Gansel et al., 2014; Klebert et al., 2013; Klebert and Su, 2020). It is suggested that the swimming pattern of the fish can attenuate and redirect the internal water currents of a cage (Johansson et al., 2007). High fish densities are seen to deflect the ambient current (Gansel et al.,

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2014), and it is hypothesized that as the fish swims in a torus shape they push the water outwards at depths of high biomass, resulting in a low pressure area in the centre drawing in water from depths above and below this area (Frank et al., 2015; Gansel et al., 2014). Simulations of fish behaviour on flow dynamics support this notion as a high density of fish swimming in a torus shape increased the maximum velocity in the upwelling flow (Tang et al., 2017). However, in the recent study by Klebert and Su (2020) there was no indication of a recirculation pattern when the cage was stocked, nor was there any evidence that the fish generated a secondary radial or vertical flow (Klebert and Su, 2020).

This reduction can lead to reduced water exchange in the fish cage, which can become problematic with regards to DO levels inside the cage, especially when current speeds are low (Winthereig-Rasmussen et al., 2016). If DO is reduced sufficiently hypoxic conditions can occur, which reduces feed intake, growth rates and fish welfare (Remen et al., 2014). The use of a non-permeable lice shielding skirt increases the blocking effect, and low DO levels inside the fish cages are reported at some locations (Stien et al., 2012).

As lice shielding skirts have a direct impact on how the current flows through the cage, and consequently the internal environment of the cage, it is necessary to investigate how cages with and without skirts differ. The aim of this study was to investigate how a lice shielding skirt influenced the DO and water flow inside a fully stocked cage, specifically the vertical motion and the reduction in current speed from outside to inside the cage. As model-scale experiments can not take into account the presence of fish and their behaviour, and comparing data from different sites with and without skirts may be of limited value due to variable topography, hydrographical conditions and different stocking densities, this study was performed at the same site and measurements were collected from the same fully-stocked fish cage during a three-day period which included the transition from a shielded to an unshielded cage.

2. Material and methods

2.1. Site description

The study took place from the 5–7th of November 2018 on the fish farm Hosnaøyan, located in the county of Trøndelag, Norway (Fig. 1). The Hosnaøyan farm consists of ten cages in a frame mooring (Fig. 2). Cages marked with horizontal and vertical lines contained fish. The cage used for the measurements (shaded cage in Fig. 2), was 157 m in circumference with a 15 m deep cylindrical net with a sinker tube at the bottom with a weight of 60 kg m^{-1}. The bottom of the cage was conical from 15 m to 28 m with a weight of 250 kg at the centre of the cone. The net had a solidity of 0.21 and a mesh opening of 17.5 mm, and was cleaned on the 1st of November, hence there was little bioufouling during this study.

The cage was equipped with a 6.7 m deep non-permeable tarpaulin shielding skirt (Botngaard AS, Oksvoll, Norway), weighted with 4 kg m^{-1} around the bottom of the skirt. The skirt was installed 16:00 on the 4th of November, the day prior to the onset of the study. Due to a sudden drop in dissolved oxygen (DO), the skirt was lifted on the 06.11.2018 09:45. The biomass in the cage during the experiments was 830 tonnes, with 189 200 fish of average weight 4.4 kg.

2.2. Equipment description

2.2.1. ADV and DCP

Current speed and direction outside the cage were recorded using an Aanderaa SeaGuard II doppler current profiler (DCP) measuring continuously with a sampling frequency of 0.5 Hz (see Fig. 2). The velocity accuracy was 0.3 cm s^{-1} or ±1% of full-scale reading, with a velocity resolution of 0.1 cm s^{-1}. The data was averaged and stored every minute. The DCP was attached to the anchoring buoy pointing downwards with vertical resolution (cell size) set to 1 m.

An ADCP Aquadopp Profiler 400kHz produced by Nortek Group was mounted on the oceanographic buoy located roughly 100 m South of the farm (OB, Fig. 2). Its velocity range was ±10 m/s and measurements were made with an accuracy of ± 1% of the measured value or ±0.5 cm s^{-1}. The ADCP had a cell size of 3 m, and a constant sampling rate of 2 Hz during the sample period of 10 min. The acquisition interval was set to 60 min, and the data was averaged over the 10 min sampling period.

The current velocity inside the cage was measured using Nortek Vector Acoustic Doppler Velocimeters (ADV) with a sampling rate of 8Hz, with 60 samples per burst and a burst interval of 60 s. The ADVs have an accuracy of 0.5% of measured value ±1 mm s^{-1}, with velocity precision typical 1% of velocity range (at 16Hz). The ADVs were suspended from a buoy at 2, 6 and 8 m depth.

The ADV-rig had a total of three positions during the study, Pos. 1 was in the centre of the cage, while Pos. 2 was to the N-E end of the cage, and Pos. 3 was to the S-W of the cage. Both Pos. 2 and 3 were roughly 8 m from the floating collar (Fig. 2). Pos. 1 and 2 were used to measure the current flow through the cage, and the reduction in current speed. While Pos. 3 was used when the skirt was lifted, and was positioned just in front of the initial lifting point of the skirt.

Raw data from the ADVs were filtered using the improved phase space filter (Goring and Nikora, 2002) for bubbly flows (Birjandi and Bibeau, 2011) to remove velocity spikes caused by Doppler noise, signal aliasing and disturbances from the fish as the cage was fully stocked. Velocity spikes were not replaced but removed. The ADV data was averaged over 1 min, and if more than 50% of the data in a minute had been removed, the entire minute was excluded from further analyses.

2.2.2. Dissolved oxygen

Dissolved oxygen (DO) was measured every minute using Aanderaa Optode 4330 oxygen sensors (Aanderaa Data Intruments AS, Bergen, Norway). The measurement range was 0 - 1000 μM (0 - 300%) with a calibration range of 0 - 500 μM (0 - 150%), resolution of < 0.5 μM (0.05%) and an accuracy of < 8 μM (5%). DO were measured both inside and outside of the cage at 3 m depth (Fig. 2). The DO sensor inside was suspended from a floating buoy 3 m from the net, while the sensor outside was mounted right outside of the floating collar. DO was sampled every minute throughout the measurement period.

The oceanographic buoy was equipped with an Aanderaa Optode 4531A (Aanderaa Data Intruments AS, Bergen, Norway). The measurement range was 0 - 800 μM (0 - 200%), with a resolution of < 1 μM (0.4%) and an accuracy of < 8 μM (5%). The optode had an averaging cycle of 1 min and acquisition interval of 60 min.

2.2.3. Echosounder

The vertical position of the fish was studied by using a Kongsberg EK15 echosounder mounted from a small buoy facing downwards at about 0.5 m depth and 8 m from the net (see Fig. 2).

3. Results and discussion

3.1. Vertical swimming behaviour and DO conditions

The lice shielding skirt was installed one day prior to this study and was removed on the 6th of November due to welfare concerns for the fish as the gradual decrease in DO during the night became steeper in the morning.

The salmon's swimming depth observed in the echogram did not appear to be influenced by the skirt (Fig. 3). The salmon swam at deeper depths during the day and were more evenly distributed in the water column, while at night they moved closer to the surface and were more clustered. This diurnal pattern is consistent with previous studies of swimming behaviour (Oppedal et al., 2011), but not with the avoidance of the skirt volume observed in (Gentry et al., 2020). One potential reason for this could be the submerged metal halide lamp (OSRAM HQI-T 1000 W/D) which was mounted at 5 m depth, roughly 5 m from the echogram and 3 m from the net. The light was turned on around sunset at 17:00, and off near sunrise 07:00. Such artificial light are known to attract salmon (Juell and Fosseidengen, 2004; Oppedal et al., 2007), and could therefore have had an effect on the behaviour seen in the echogram after sunset. However, Gentry et al. (2020) also used underwater lighting and unlike in this study, saw a difference in swimming depth in the cage with skirt and those without. It should be noted that in Gentry et al. (2020) a permeable skirt was used and it is possible that this skirt would facilitate different swimming behaviour than a non-permeable one, or that the swimming behaviour was influenced by the combination of local conditions and presence of skirt.

The DO level inside the cage and just outside the cage varied together throughout the period (Fig. 3). The DO at the oceanographic buoy was more consistent, however, it should be noted that it only recorded DO every hour. At some instances, the DO sensor inside the fish cage recorded higher levels than the sensors just outside of the cage. This is probably due to non-optimal placement of the DO-sensor outside of the cage. It is possible that when the current was heading towards N-E that the sensor was positioned in the wake of the cage as it was lowered just outside of the floating ring. The oceanographic buoy may therefore be a better reference point, despite low temporal resolution.

Roughly three hours prior to the lifting of the skirt the fish appear to spread more evenly throughout the cage volume, indicating an increase in activity as the sun rose. The sudden drop in DO from 8 AM could be due to onset of feeding and an increase in swimming activity as swimming speeds are generally higher during the day than at night (Oppedal et al., 2011), and an increase in swimming speed will increase the oxygen consumption (Hvas et al., 2017). Another possible reason for the drop in DO was the weak current during this period as the current appeared to be turning from N-E to S-W (Fig. 3).

A weaker drop in internal DO was seen the 7th of November around 9 AM when there was no skirt deployed (just after Case 2 in Fig. 3). Conditions were similar to the previous drop on the 6th of November, with weak current speed, current direction turning from N-E to S-W and the salmon more evenly spread vertically (Fig. 3). This drop was not as steep nor as severe as the previous day, when the skirt was deployed. It is possible that the combination of the turning current and the increased activity are the main causes for the observed drops in DO.

The results in Fig. 3 indicate that the presence of the skirt intensified the DO drop, but as the skirt had to be removed on the 6th of November, it is uncertain whether DO would have improved with time without the removal of the skirt. The DO just outside had begun to improve prior to the skirt removal, but there was no improvement seen on the sensors inside the cage at this time. The DO dropped to a minimum of 59% when the skirt was on, but did not drop below 69% when the skirt had been lifted. As smaller salmon are more susceptible to hypoxic conditions than large fish (Oldham et al., 2019) and the average water temperature was only 9 °C, it is unlikely that the salmon was harmed by the low DO. However, a DO in the range of 45–55% results in reduced aerobic metabolic capacity and swimming performance also in large salmon (Oldham et al., 2019). Had the DO level continued to decrease it may have posed a threat to the welfare of the salmon.

3.2. Lifting of the skirt

Echogram and DO were recorded during the entire deployment, and thereby also during the transition when the skirt was lifted. The skirt was lifted by use of a crane on a working boat S-W of Pos. 3 (Fig. 2). The skirt removal operation started at 09:48 and was completed by 10:35. During the procedure, the ADV-rig was placed in Pos. 3, and the average current speed in this position and in the DCP during this period are presented in Table 1. As explained previously, the low current speed in the DCP can be explained by the turning current, evident in the direction at the different depths (Table 1) and in the OB (Fig. 3).

When the removal of the skirt was initiated at 09:48 the DO inside the cage was 6.9 Mg/L, equivalent to 59% DO. The DO inside the cage started improving after 9 minutes, and the DO reached 9.5 Mg/L, that is 81%, inside the cage after another 20 minutes. At this point the DO just outside the cage was 84%. It took in total 30 minutes from the lifting was initiated to the DO level inside the cage reaching similar levels as outside and at the OB (Fig. 3).

3.3. Current flow through the cage

The main direction of the current at Hosnaøyan is controlled by the local bathymetry along the North-Easterly isobaths (Fig. 2). To isolate the influence the skirt had on the current flow, it was necessary to find episodes having similar incoming current conditions when the cage was with and without the skirt. Two 3-hour periods were deemed usable for this purpose, one for each condition. The criteria required that the current had to be moving along the depth isobaths (see Fig. 1) and the current had to be reasonably stable and unobstructed by surrounding farm structures. Hence only data where the average hourly current direction was aligned with the depth isobaths towards 45–90 degrees (North-East to East) was included. As an additional requirement the hourly current direction at the DCP had to deviate less than ±25 degrees from the current direction measured at the oceanographic buoy in the same period. The two relevant episodes are arranged into two cases and are listed in Table 2. These cases are used to investigate the current flow through the cage and speed reduction. Average weather conditions during these two cases were recorded at the oceanographic buoy and are listed in Table 3.

As evident from Fig. 3, the current velocity was not homogeneous with depth, and the DCP data indicates that the frame mooring may have been in line of sight of the sensor at 8 m depth. To compare the current outside the cage with the current inside, data from similar depths had to be applied. The reference for the velocity measured by the ADV at 2 m depth was the first cell of the DCP which averages over the depths from 2 to 3 m. While the reference velocity for the ADVs at 6 and 8 m was the average current speed recorded by the DCP from 5 to 6 m and from 6 to 7 m (Cell 4 and 5).

The current data from the DCP and the ADVs for the cases described in Table 2 are shown in Fig. 4 – 5. It is important to note that the ADV in Case 2 was placed in Pos. 2, roughly 8 m from the cage net, while the measurements for Case 1 were taken from the centre of the cage.

For Case 1 the direction of the current measured outside and inside the cage at 6 and 8 m depth were similar. The velocity direction within the skirt volume, recorded at 2 m depth, agreed with the main current direction but was more scattered. There was a weak positive vertical component in the ADVs towards the surface in Case 1. This trend was seen in all of the ADVs, but there was a larger variance for the ADV at 2 m depth (Fig. 4).

For Case 2 there was good agreement regarding direction of the current within the cage and in the DCP outside at all depths. Unlike Case 1, there was a weak downward component in the ADVs at 2 and 8 m depth, while the ADV at 6 m depth did not have a clear vertical component. It should be noted that in Case 2 the ADVs were positioned closer to the cage net, and the downward component could be an effect of its position.

It is unlikely that the positive vertical component in Case 1 was caused by vertical motion in the buoy as the waves were small at the

Table 1
Average horizontal speed and direction in DCP and ADV during lifting of the skirt between 09:48 and 10:55 on the 6th of November.

	DCP		ADV	
	Horizontal Speed [cm/s] (+/- STD)	Direction	Horizontal Speed [cm/s] (+/- STD)	Direction
2m	6.0 (±3.5)	10	6.5 (±2.9)	60
6m	5.3 (±2.8)	273	7.3 (±4.5)	286
8m	6.0 (±2.5)	250	7.8 (±4.7)	270

Table 2
Description of cases including ADV position and time intervals.

Case	ADV Position	Skirt condition	Date	Time interval
1	1	Down	5.11.2018	17:00 - 20:00
2	2	Lifted	7.11.2018	06:00 - 09:00

Table 3
Wave and current conditions measured at oceanographic buoy during cases described in Table 2. Following convention, North is defined as 0°, and East as 90°, with wave direction defined as the direction the wave is coming from, while current direction defined as the direction the current moving towards.

Wave				Current	
Case	Direction (deg)	Period (s)	Height (m)	Speed (m/s)	Direction (deg)
1	290	4.5	0.17	0.21	67
2	22.3	6.8	0.21	0.16	69

oceanographic buoy (Table 3). It is however possible that the high density of the fish in the upper layers during Case 1 (see echogram Fig. 3) could have resulted in the pumping effect, that is, the circular swimming pattern of the fish that causes an area with lower pressure drawing in water from below and above, described by Gansel et al. (2014) and Tang et al. (2017). However, the horizontal swimming behaviour was not observed during this study and it can thus not be confirmed that the fish were swimming in a torus shape. In Klebert and Su (2020) a vertical upwelling was seen in a shielded cage at 1.5 m depth within the skirt volume, but not beneath the skirt volume at 12 m depth. This upwelling was observed in a shielded cage independently if it was stocked or not (Klebert and Su, 2020). Hence the most likely explanation for the positive vertical current component during Case 1 is the skirt itself, and not the biomass.

3.4. Reduction in current speed

For Case 1 and 2, the reduction of the current speed through the cage

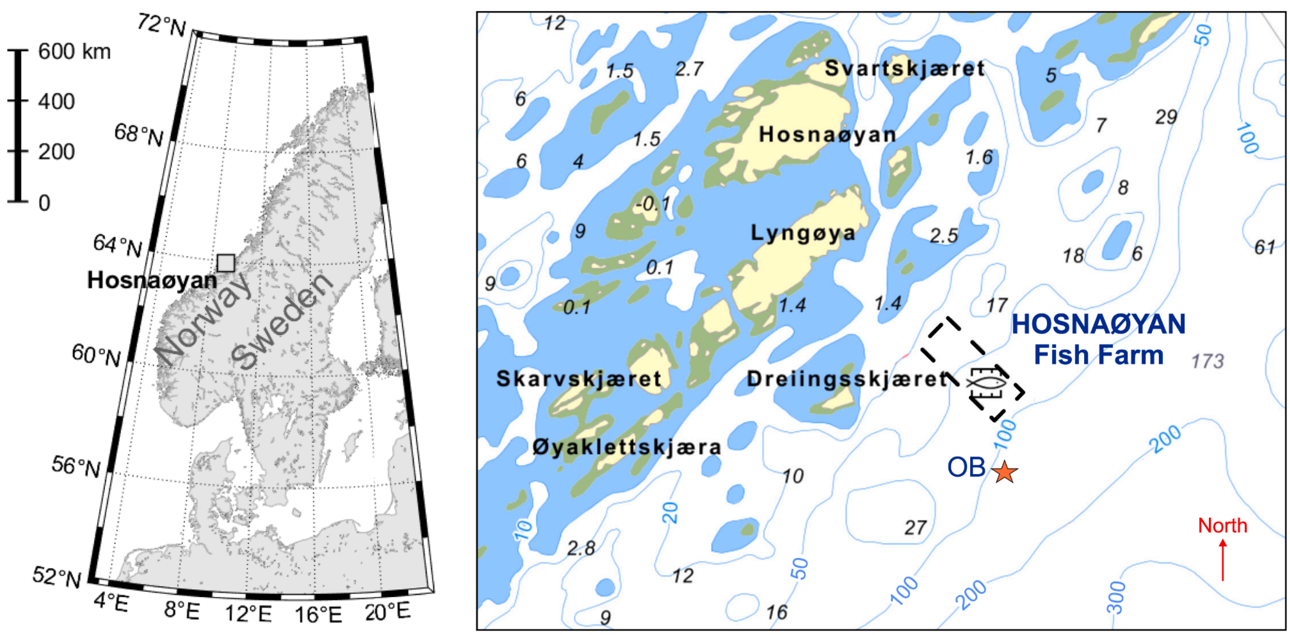

Fig. 1. Location of the fish farm at Hosnaøyan, where the measurement campaign was carried out in November 2018.

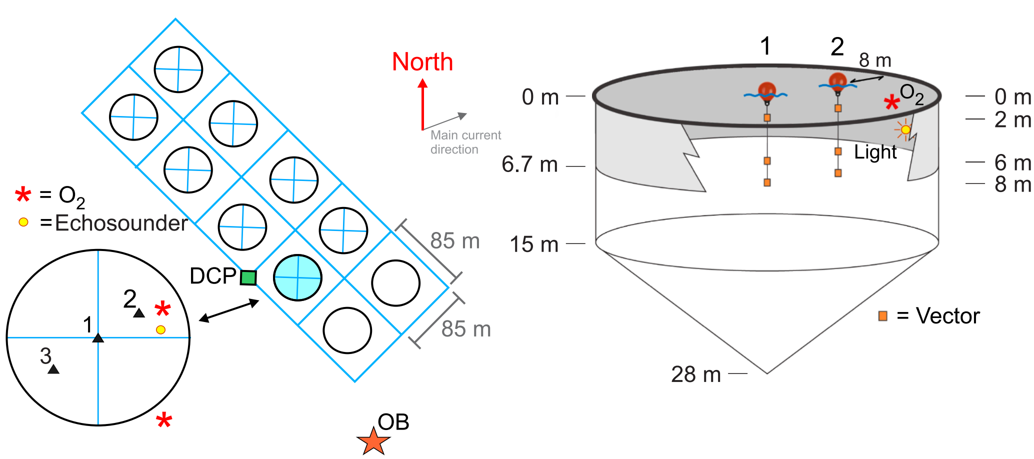

Fig. 2. Instrument placement at Hosnaøyan. The shaded cage was used as the experimental cage. The Aanderaa current profiler (DCP) was placed at the square marked DCP. The vector current meters (ADV) were moved between the two positions 1 and 2. Three ADVs were used, positioned at 2, 6 and 8 m depth suspended from a floater held in place with ropes attached to the cage ring. Two dissolved oxygen (DO) sensors were deployed, one on the inside also suspended from a floater 3 m from the cage ring, and one outside of the cage suspended from the cage ring (marked with *), both at 3 m depth. A light source was mounted at 5 m depth inside the cage. The position of the oceanographic buoy (OB) is marked with a star. The main current direction during Case 1 and 2 described in 3.3 is also marked just beneath the North sign.

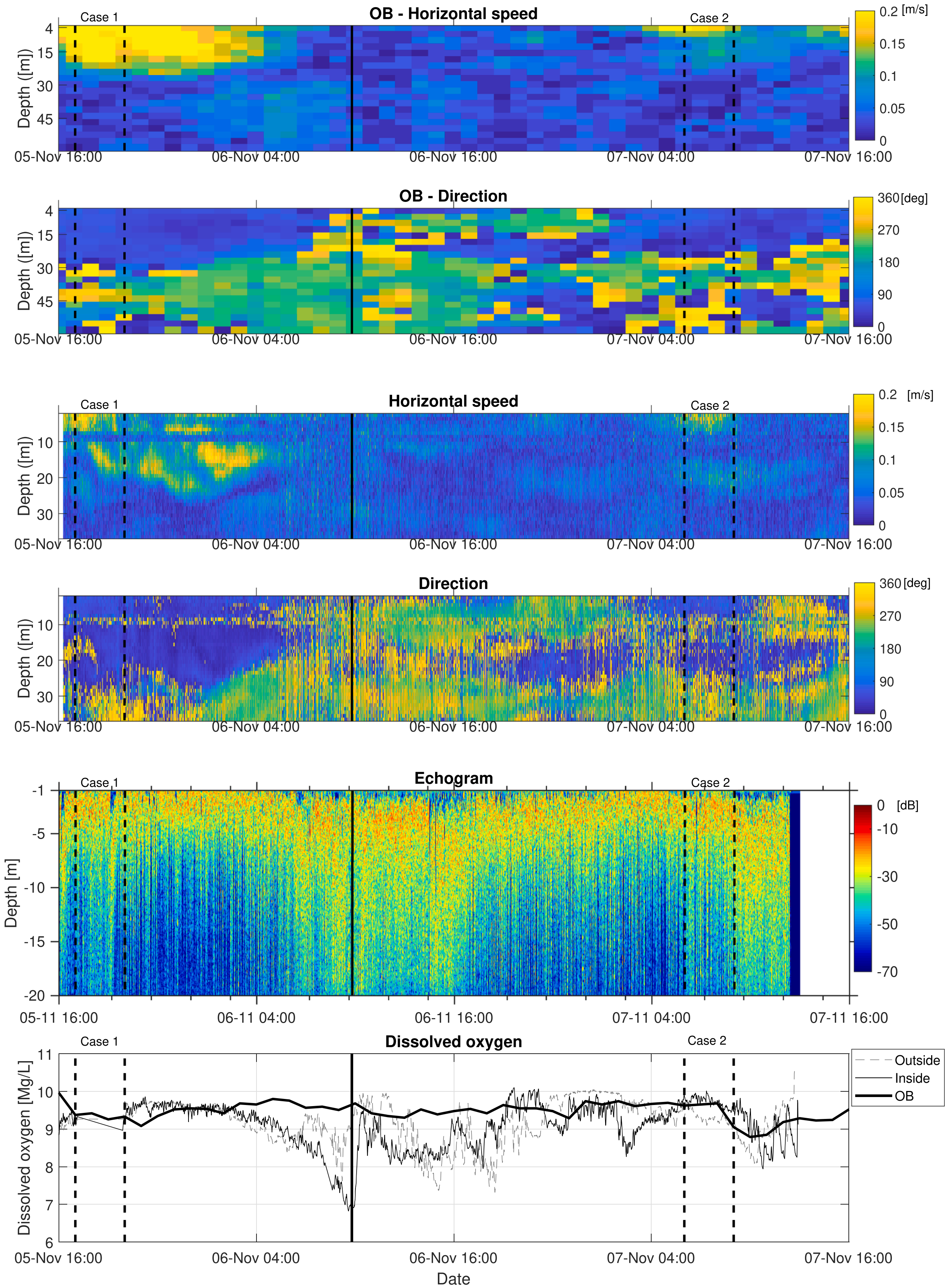

Fig. 3. Horizontal current speed and direction recorded for the entire period in the oceaographic buoy (OB) and in the DCP. Acoustic backscattering strength (S_v) measured in the echosounder. Dissolved oxygen in Mg/L recorded inside and outside of the cage, and at the OB. Case 1 and Case 2 are marked with dotted lines, while the vertical line marks the period where the lifting of the skirt was initiated.

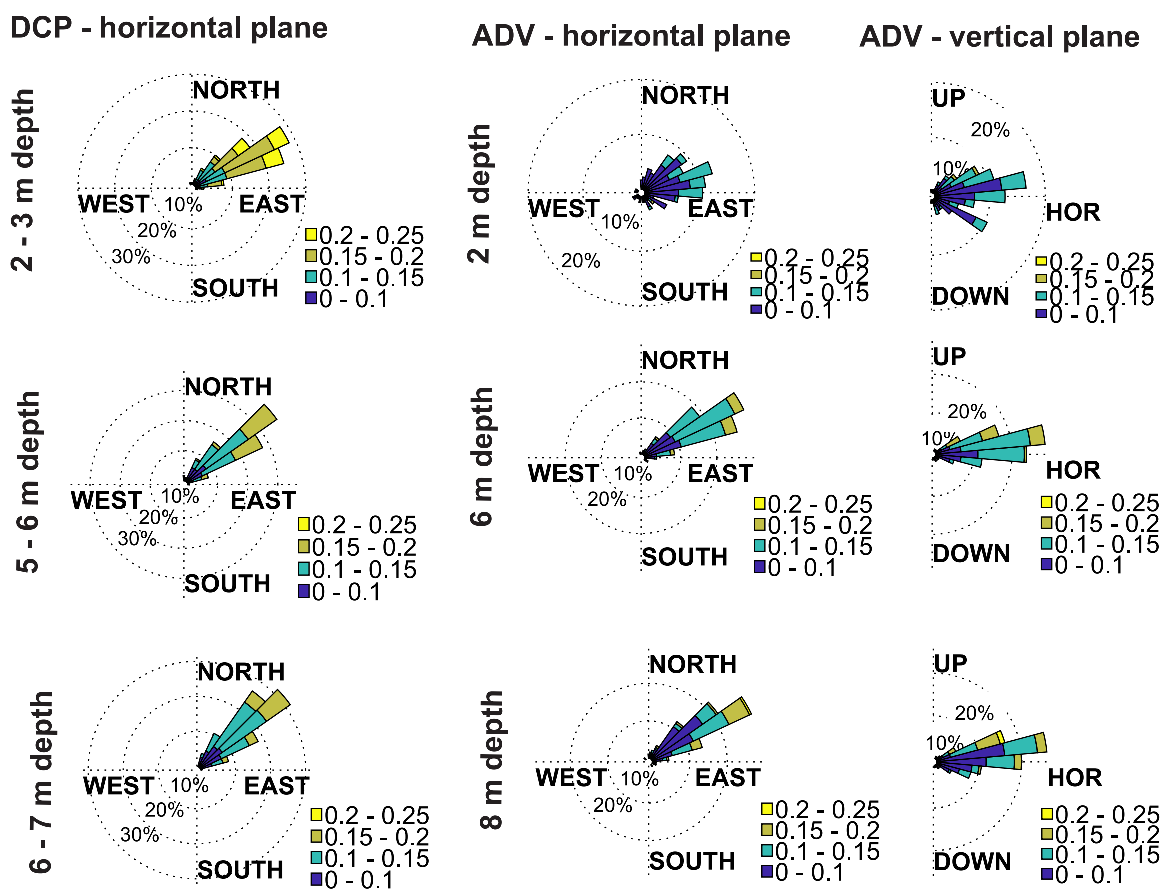

Fig. 4. Polarplots for current data for Case 1: With skirt down. The first column shows the horizontal speed in the DCP outside of the cage in [m/s], while the other two columns show the current data recorded by the ADVs in Pos. 1 inside the cage (centre of the cage, see Fig. 1). The middle column shows the horizontal speed, while the column to the right shows the current speed in the vertical plane inside the cage.

was calculated by comparing the ADVs with the measurements taken by the DCP outside the cage. The mean horizontal speed was calculated over 20-min intervals before the reduction in current speed was calculated. The average reduction in current speed for both cases are listed in Table 4.

The ADV placed at 2 m depth in the shielded cage had the highest mean reduction in current speed compared to the current in the DCP outside (56.9%, Table 4), and recorded the highest reduction of 86% during one of the 20-minute intervals when the current speed outside was 18.6 cm s^{-1}. This is a high reduction rate, but not unheard of for shielded cages. A reduction of 61% is observed downstream of an empty shielded cage (Klebert and Su, 2020). For empty unshielded cages the reduction from upstream to inside the cage is 21.5% (Klebert et al., 2015). This reduction is expected to be higher for stocked cages as in a stocked model-scale cage the reduction was 31%, although it was theorized that this increased reduction was due to biofouling (DeCew et al., 2013). A higher reduction was found in the unshielded stocked cage observed in Johansson et al. (2014), but the reduction varied with current speed, and within the same reference current speed. For instance, the reduction could vary from 0 to 50% when the current speed outside was 20 cm s^{-1} (Johansson et al., 2014). The stocking density in Johansson et al. (2014) was much lower at 6.2 kg m^{-3}, compared to 21.9 kg m^{-3} in this study, hence with the addition of a shielding skirt a reduction of 86% during a 20-minute interval is plausible.

The reduction at 2 m in Case 2 is higher than expected with a maximum reduction of 51% when the current speed was 14 cm s^{-1} outside. The high reduction rate in Case 2 could be influenced by the rig's position, as a near linear reduction in current speed is seen through unshielded and empty cages in experiments and simulations (Klebert et al., 2015; Patursson, 2008; Winthereig-Rasmussen et al., 2016). It is possible that a similar effect has occurred, despite the cage being stocked, hence the reduction for Case 2 might have been lower had the ADV-rig been placed in the centre. This is also valid for the sensors at 6 and 8 m depth. However, this effect does not appear for the sensor at 8 m depth, with Case 2 having a lower reduction rate than Case 1. It is therefore more likely that the high reduction at 2 m in Case 2 is due to the biomass. From the echosounder it appears the highest density of fish during Case 1 and 2 were close to the surface in the top 5 m (Fig. 3). The average reduction in Case 2 at 2 m was also close to that of DeCew et al. (2013) of 32%, however it should be noted that DeCew et al. (2013) used a model-scaled cage with fewer fish.

The reduction at 6 and 8 m in Case 1 and 2 were slightly lower than the reduction of 21.5% in Klebert et al. (2015) despite the cage being stocked. The low reduction at 6 m depth in Case 1 could be explained by the current flow being forced underneath the skirt and into the cage, as seen in dye experiments (Frank et al., 2015) and simulations (Lien et al., 2015). When pressed underneath the skirt, the water accelerates (Lien et al., 2015), which may have caused the lower reduction rate when the skirt was deployed.

The low average reduction rates at 6 and 8 m during Case 2 however could be accounted to the large variation in reduction, as seen by the standard deviation (Table 4), or due to low current speeds outside of the cage. As average current decreased with depth, the strongest currents were those at 2 m depth. This could explain why the reduction in speed decreases with depth for Case 2. It should also be noted that the 21.5% in Klebert et al. (2015) was recorded at the Faroe Islands where the minimum current speed was 0.15 m/s and the maximum over 0.5 m/s. Higher current velocities will result in larger deformations, and thereby

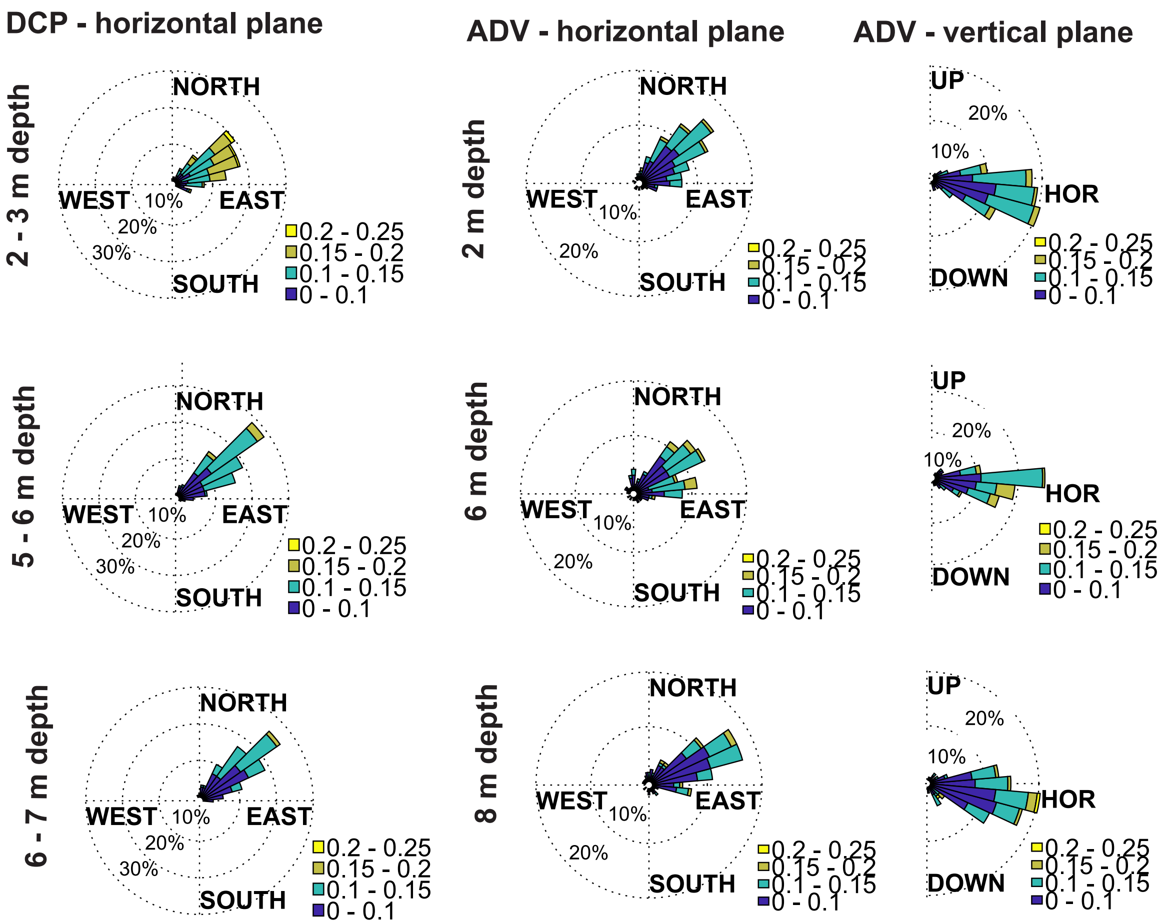

Fig. 5. Polarplots for current data for Case 2: Without skirt. The first column shows the horizontal speed in the DCP outside of the cage in [m/s], while the other two columns show the current data recorded by the ADVs in Pos. 2 inside the cage (see Fig. 1). The middle column shows the horizontal speed, while the column to the right shows the current speed in the vertical plane inside the cage.

Table 4
Mean reduction through cage for each depth for the two cases with and without skirt. Readers should note that the ADV in Case 1 is located in position 1, while it is position 2 in Case 2.

	Mean reduction [%] (± STD)	
Depth	Case 1 (with skirt)	Case 2 (without skirt)
2m	56.9 (± 21.4)	32.0 (± 12.3)
6m	10.4 (± 15.1)	17.9 (± 19.5)
8m	18.6 (± 16.0)	14.6 (± 18.0)

increased solidity of the cage net (Lader et al., 2008). The results from this study may therefore not be applicable at higher velocities.

4. Conclusion

In this study data was collected from a fully stocked cage with high biomass. The current inside the shielded cage had a positive vertical component towards the surface at all depths in the centre of the cage, which was not the case when the skirt was removed and the ADVs were placed closer to the net wall. The reduction in current speed from outside to inside of the cage agree fairly well with previous findings beneath the skirt volume. Only the ADV at 2m depth showed a clear effect of the skirt, with an average reduction of 56.9% when the skirt was deployed in Case 1 compared to 32% when the skirt was removed in Case 2.

There was no clear distinction in behaviour of the salmon during the study when the skirt was deployed. The DO varied throughout the study, however the sudden drop in DO when the skirt was deployed can be explained by the obstruction of the current by the skirt, increased fish activity and low current speed from a non-optimal direction. When the skirt was removed the DO improved from 59% to 81% within 30 minutes despite weak currents, exemplifying the importance of continuous monitoring of DO when using skirts.

CRediT authorship contribution statement

Kristbjörg Edda Jónsdóttir: Conceptualization, Investigation, Data curation, Visualization, Writing - original draft. **Zsolt Volent:** Conceptualization, Investigation, Funding acquisition, Project administration, Writing - original draft. **Jo Arve Alfredsen:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abolofia, J., Asche, F., Wilen, J.E., 2017. The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. Mar. Resour. Econ. 32 (3), 329–349.

Bi, C.-W., Zhao, Y.-P., Dong, G.-H., Xu, T.-J., Gui, F.-K., 2013. Experimental investigation of the reduction in flow velocity downstream from a fishing net. Aquacult. Eng. 57, 71–81.

Birjandi, A.H., Bibeau, E.L., 2011. Improvement of acoustic doppler velocimetry in bubbly flow measurements as applied to river characterization for kinetic turbines. Int. J. Multiphase Flow 37 (8), 919–929.

DeCew, J., Fredriksson, D., Lader, P., Chambers, M., Howell, W., Osienki, M., Celikkol, B., Frank, K., Høy, E., 2013. Field measurements of cage deformation using acoustic sensors. Aquacult. Eng. 57, 114–125.

Frank, K., Gansel, L., Lien, A., Birkevold, J., 2015. Effects of a shielding skirt for prevention of sea lice on the flow past stocked salmon fish cages. J. Offshore Mech. Arct. Eng. 137 (1).

Gansel, L.C., Plew, D.R., Endresen, P.C., Olsen, A.I., Misimi, E., Guenther, J., Jensen, Ø., 2015. Drag of clean and fouled net panels–measurements and parameterization of fouling. PLoS ONE 10 (7), e0131051.

Gansel, L.C., Rackebrandt, S., Oppedal, F., McClimans, T.A., 2014. Flow fields inside stocked fish cages and the near environment. J. Offshore Mech. Arct. Eng. 136 (3).

Geitung, L., Oppedal, F., Stien, L.H., Dempster, T., Karlsbakk, E., Nola, V., Wright, D.W., 2019. Snorkel sea-cage technology decreases salmon louse infestation by 75% in a full-cycle commercial test. Int. J. Parasitol. 49 (11), 843–846.

Gentry, K., Bui, S., Oppedal, F., Dempster, T., 2020. Sea lice prevention strategies affect cleaner fish delousing efficacy in commercial atlantic salmon sea cages. Aquac Environ Interact 12, 67–80.

Goring, D.G., Nikora, V.I., 2002. Despiking acoustic doppler velocimeter data. J. Hydraul. Eng. 128 (1), 117–126.

Heuch, P.A., Parsons, A., Boxaspen, K., 1995. Diel vertical migration: a possible host-finding mechanism in salmon louse (Lepeophtheirus salmonis) copepodids? Can. J. Fish. Aquat.Sci. 52 (4), 681–689.

Hevrøy, E., Boxaspen, K., Oppedal, F., Taranger, G., Holm, J., 2003. The effect of artificial light treatment and depth on the infestation of the sea louse lepeophtheirus salmonis on atlantic salmon (Salmo Salar L.) culture. Aquaculture 220 (1–4), 1–14.

Huse, I., Holm, J., 1993. Vertical distribution of atlantic salmon (salmo salar) as a function of illumination. J. Fish Biol. 43, 147–156.

Hvas, M., Folkedal, O., Imsland, A., Oppedal, F., 2017. The effect of thermal acclimation on aerobic scope and critical swimming speed in atlantic salmon, salmo salar. J. Exp. Biol. 220 (15), 2757–2764.

Iversen, A., Hermansen, Ø., Nystøyl, R., Hess, E.J., 2017. Kostnadsutvikling i lakseoppdrett-med fokus på fôr-og lusekostnader. Nofima rapportserie.

Johansson, D., Juell, J.-E., Oppedal, F., Stiansen, J.-E., Ruohonen, K., 2007. The influence of the pycnocline and cage resistance on current flow, oxygen flux and swimming behaviour of atlantic salmon (salmo salar l.) in production cages. Aquaculture 265 (1–4), 271–287.

Johansson, D., Laursen, F., Fernö, A., Fosseidengen, J.E., Klebert, P., Stien, L.H., Vågseth, T., Oppedal, F., 2014. The interaction between water currents and salmon swimming behaviour in sea cages. PLoS ONE 9 (5), e97635.

Juell, J.-E., Fosseidengen, J.E., 2004. Use of artificial light to control swimming depth and fish density of atlantic salmon (salmo salar) in production cages. Aquaculture 233 (1–4), 269–282.

Klebert, P., Lader, P., Gansel, L., Oppedal, F., 2013. Hydrodynamic interactions on net panel and aquaculture fish cages: a review. Ocean Eng. 58, 260–274.

Klebert, P., Patursson, Ø., Endresen, P.C., Rundtop, P., Birkevold, J., Rasmussen, H.W., 2015. Three-dimensional deformation of a large circular flexible sea cage in high currents: field experiment and modeling. Ocean Eng. 104, 511–520.

Klebert, P., Su, B., 2020. Turbulence and flow field alterations inside a fish sea cage and its wake. Appl. Ocean Res. 98, 102113.

Lader, P., Dempster, T., Fredheim, A., Jensen, Ø., 2008. Current induced net deformations in full-scale sea-cages for atlantic salmon (Salmo Salar). Aquacult. Eng. 38 (1), 52–65.

Lien, A.M., Høy, E., 2011. Skjørt for Skjerming mot lus i Laksemerd. Technical Report. SINTEF Fiskeri og Havbruk AS, Brattørkaia 17c, 7010, Trondheim Norway.

Lien, A.M., Stien, L.H., Grøntvedt, R., Frank, K., 2015. Permanent skjørt for redusering av luspåslag på laks. Technical Report. SINTEF Fiskeri og Havbruk AS, Brattørkaia 17c, 7010, Trondheim Norway.

Lien, A.M., Volent, Z., Jensen, Ø., Lader, P., Sunde, L.M., 2014. Shielding skirt for prevention of salmon lice (Lepeophtheirus Salmonis) infestation on atlantic salmon (Salmo Salar L.) in cages–a scaled model experimental study on net and skirt deformation, total mooring load, and currents. Aquacult. Eng. 58, 1–10.

Oldham, T., Nowak, B., Hvas, M., Oppedal, F., 2019. Metabolic and functional impacts of hypoxia vary with size in atlantic salmon. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 231, 30–38.

Oppedal, F., Dempster, T., Stien, L.H., 2011. Environmental drivers of atlantic salmon behaviour in sea-cages: a review. Aquaculture 311 (1–4), 1–18.

Oppedal, F., Juell, J.-E., Johansson, D., 2007. Thermo-and photoregulatory swimming behaviour of caged atlantic salmon: implications for photoperiod management and fish welfare. Aquaculture 265 (1–4), 70–81.

Oppedal, F., Samsing, F., Dempster, T., Wright, D.W., Bui, S., Stien, L.H., 2017. Sea lice infestation levels decrease with deeper 'snorkel'barriers in atlantic salmon sea-cages. Pest Manag. Sci. 73 (9), 1935–1943.

Patursson, Ø., 2008. Flow through and around fish farming nets. Ocean Engineering, University of New Hampshire, Durham, NH03824, USA.

Rasmussen, H.W., Patursson, Ø., Simonsen, K., 2015. Visualisation of the wake behind fish farming sea cages. Aquacult. Eng. 64, 25–31.

Remen, M., Aas, T.S., Vågseth, T., Torgersen, T., Olsen, R.E., Imsland, A., Oppedal, F., 2014. Production performance of atlantic salmon (Salmo Salar L.) postsmolts in cyclic hypoxia, and following compensatory growth. Aquac. Res. 45 (8), 1355–1366.

Stien, L.H., Nilsson, J., Hevrøy, E.M., Oppedal, F., Kristiansen, T.S., Lien, A.M., Folkedal, O., 2012. Skirt around a salmon sea cage to reduce infestation of salmon lice resulted in low oxygen levels. Aquacult. Eng. 51, 21–25.

Tang, M.-F., Xu, T.-J., Dong, G.-H., Zhao, Y.-P., Guo, W.-J., 2017. Numerical simulation of the effects of fish behavior on flow dynamics around net cage. Appl. Ocean Res. 64, 258–280.

Winthereig-Rasmussen, H., Simonsen, K., Patursson, Ø., 2016. Flow through fish farming sea cages: comparing computational fluid dynamics simulations with scaled and full-scale experimental data. Ocean Eng. 124, 21–31.