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Flow through fish farming sea cages: Comparing computational fluid dynamics simulations with scaled and full-scale experimental data

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ABSTRACT

Computational fluid dynamics (CFD) simulations were performed on the flow through and around full-scale sea cages. The Reynolds average Navier–Stokes equations were solved using a finite volume approach. The realizable $k - \epsilon$ model was used to describe turbulence and porous media to represent the flow resistance effect of the net. Velocity deficit was investigated for a single cage, a row of five cages, and two rows of five cages, corresponding to the salmon farm at Gulin in the Faroe Islands. CFD simulations were compared with field measurement data from this farm. The comparison showed that the flow was overpredicted with up to 50% by the CFD simulations using a net solidity corresponding to the net specifications. A hypothesis is presented for the discrepancy between CFD simulations and field measurements, which includes net deformation and fish behavior. Using different cage layouts, different distances between cage centres, and different net soldities, the effects on flow through and around sea cages were examined and discussed.

1. Introduction

The demand for sustainable fish products is ever-increasing and aquaculture has become a main supplier. The production of farmed salmon is showing a stagnating trend in the northern hemisphere (Jones, 2015). One reason, among others, is the lack of coastal space suitable for salmon farming. In the Faroes most of the suitable areas are operational, so in order to expand production the farmers seek more exposed locations or to optimise production on operational farm sites, without leaving a greater biological footprint.

Contributing factors to the stagnation include parasite infections, oxygen deficits, and waste pollution. Some of the more sheltered farm sites experience periods of low oxygen levels. This can induce stress in the fish and lead to deteriorated health and appetite (Oppedal et al., 2011), making the fish more susceptible to severe parasite outbreaks. Low ability to degrade/dissolve waste pollution, i.e. the biological footprint of the fish farming, on sheltered farm sites limits the amount of fish that can be produced (Norði et al., 2011). Being able to perform an accurate simulation of the flow through fish farm sites is a strong tool in overcoming the problems stated above.

Recent field experiments, using boat-mounted acoustic Doppler current profilers (ADCP) and Kriging interpolation, have produced a detailed flow field in the wake of an Atlantic Salmon (Salmo salar) farm site (Winthereig-Rasmussen and Oystein Patursson, 2015). The method has the potential to produce measurements, which can be used as verification of CFD simulations of flow through and around aquaculture farm sites. It has applications in sectors where one seeks full-scale field data of velocity deficit in the wake of bluff bodies, such as the tidal energy and the aquaculture sector. At the same farm site, Klebert et al. (2015) performed measurements of cage deformation and flow velocities inside and outside a net cage over a period of 3 months, overlapping the measurements performed by Winthereig-Rasmussen and Oystein Patursson (2015).

There have been some CFD studies of flow through and around an aquaculture cage of the gravity type (Patursson, 2008; Zhao et al., 2013; Bi et al., 2014). Patursson et al. (2010) introduced a method of substituting the cage nets with a porous media in CFD simulation. They performed experimental measurements on velocity deficit in the wake of a net panel at different angles of attack. The results were transformed into porous media coefficients, which could be implemented in a CFD simulation. Patursson also did measurements on the velocity deficit in the wake of a scale model octagonal aquaculture sea cage of the gravity type (Patursson, 2008). He compared the results with a CFD simulation of flow through the same cage, using porous media as a substitute for the net. Zhao et al. (2013) did a study of up to four cages in a row and looked at velocity reduction through the centre line of the cages. They found only minor flow variation inside the cages by increasing distance between cages. Zhao et al. (2015) recently

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published an experimental study on flow velocity and mooring loads on scaled net cages arranged in single and double rows with up to eight cages. However all these CFD simulations have been performed on scaled cages, which have been verified with experimental measurements in flumes and tow tanks. Cornejo et al. (2014) performed large Eddie simulations (LES) of a full scale salmon farm in a constant flow and in a semidiurnal tidal current. The model did not include bathymetry data and there were no field measurement data to validate the LES simulation.

In this paper an attempt is made to perform a CFD simulation of the flow through a full-scale commercial salmon farm based on experience gained from previous laboratory experiments and scaled cage simulations (Patursson, 2008; Patursson et al., 2010), and to compare the CFD simulation with field measurements made at the same farm (Winthereig-Rasmussen and Oystein Patursson, 2015; Klebert et al., 2015; Johansson et al., 2014). The focus is on the flow in and around the cages, while potential effects of the relatively flat bottom and the shoreline are not included, but left for further work.

The applied model is described in Section 2, and the location, fish farm, and available data for validation are presented in Section 3. In Section 4 assessment of model parameters and optimisation of the model through mesh sensitivity investigation of flow through a single cage as well as a farm layout are given, and the simulation cases are presented. The results are given in Section 5 and discussed in the following section with emphasis on derived shortcomings when moving numerical simulations from laboratory and scaled cages to a full commercial large salmon farm in production. The paper is concluded in Section 7.

2. Model

CFD simulations were performed using the commercial software ANSYS FLUENT (ANSYS, 2014). Reynolds average Navier–Stokes (RANS) equations were used to describe the flow in the computational domain. The governing equations are the momentum equation

$$\frac{du_i}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + g_i + \frac{\partial}{\partial x_j}\nu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) + \frac{1}{\rho}S_i \tag{1}$$

and the continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

Einstein notation is applied. u_i is the velocity components, x_i the spatial coordinates, g_i the gravitational force, ρ the density of the fluid and S_i is a source term describing the resistance of the net. ν_{eff} is calculated as μ_{eff}/ρ where $\mu_{eff} = \mu + \mu_t$, P is calculated from the pressure p as $P = p + \frac{2}{3}\rho k$, where $k = u_{rms}^{\prime 2}$ and u'_{rms} is the root mean square of the turbulent velocity fluctuations.

The realizable $k - \epsilon$ turbulence model presented by Shih et al. (1995) was chosen in order to close the equation system for turbulence.

The net in the cages is substituted with a porous media in the CFD model, where the resistance parameters are implemented in the source term as follows

$$S_i = -D_{ij}\mu u_j - \frac{1}{2}C_{ij}\rho u_{mag} u_j \tag{3}$$

u_{mag} being the magnitude of the fluid velocity, D_{ij} and C_{ij} being material matrices describing the resistance coefficients in the three local principal axes of the porous media, which if x_1 is the normal to the net plane, have the following form

$$D_{ij} = \begin{bmatrix} D_n & 0 & 0 \\ 0 & D_t & 0 \\ 0 & 0 & D_t \end{bmatrix} \tag{4}$$

and

$$C_{ij} = \begin{bmatrix} C_n & 0 & 0 \\ 0 & C_t & 0 \\ 0 & 0 & C_t \end{bmatrix} \tag{5}$$

In case the local axes of the porous media are not aligned with the global coordinate system, it must be rotated by means of a tensor rotation approach.

A SIMPLEC scheme (van Doormaal and Raithby, 1984) was used for the pressure-velocity coupling, with no skewness correction. A second-order upwind spatial discretisation was used for the momentum equation, turbulent kinetic energy and turbulent dissipation rate, least squares cell based formulation for the gradient and PRESTO for the pressure.

Standard wall function was used on the bottom of the domain and frictionless wall boundary was specified for the vertical sides perpendicular to the inlet/outlet boundary and to the top boundary (Fig. 3). Velocity and turbulence properties k and ϵ were specified at the inlet boundary and were uniform across the entire face.

2.1. Løland's velocity reduction

Løland (1991) derived a theoretical expression for predicting the velocity reduction behind a net panel.

$$\frac{u}{U_0} = 1 - 0.46C_d \tag{6}$$

u being the flow velocity in the wake, U_0 the free flow velocity and C_d the drag coefficient of the net, which is calculated as

$$C_d = 0.04 + (-0.04 + 0.33S + 6.54S^2 - 4.88S^3)\cos\alpha' \tag{7}$$

The solidity (S) of the net is found using

$$S = \frac{2d_{twine}}{\lambda} - \frac{1}{2}\left(\frac{d_{twine}}{\lambda}\right)^2 \tag{8}$$

With d_{twine} as the twine diameter and λ as the length of one mesh bar between twine intersections. α' is the angle of attack (α) of the incoming flow relative to the net and is calculated as $\alpha' = \frac{\pi}{2} - \alpha$.

3. Data

3.1. Fish farm layout

The salmon farm at Gulin is situated in the bay just outside the capital of the Faroe Islands, Trshavn, and during the field measurements consisted of ten sea cages of the gravity type (Fig. 1). Two cages had a circumference of 160 m (cage no. 2 and 10 in Fig. 2), which corresponds to a diameter of about 50 m (D). The rest of the cages had a circumference of 128 m, corresponding to a diameter of about 40 m (d). The cages were positioned in a 2 × 5 grid formation with 70 m between the cage centres. The short side of the 2 × 5 cage grid was perpendicular to the flow direction and the long side approximately parallel to the shore (Fig. 2).

The row closest to the shore (cages no. 1, 3, 5, 7 and 9) is referred to as the inner row of cages and the opposite row (cages no. 2, 4, 6, 8 and 10) is referred to as the outer row of cages. The gravity cages stood with vertical net sides of 13 m length and a conical bottom net extending down to a depth of 22 m. The net