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Research Paper

Qualifying the design of a floating closed-containment fish farm using computational fluid dynamics

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In order to overcome the environmental consequences of traditional net pens in producing Atlantic salmon, closed containment aquaculture systems are being developed, where the culture volume is separated from the ambient environment by an impermeable wall. However, several challenges in terms of construction and hydrodynamic properties must be solved before such systems can be used on a large scale. A study was thus performed on the design of a floating closed-containment fish farm in sea. This paper presents the design and flow analysis of two versions of the globe; first is the pilot design of a 74 m^3 globe, and the second is the design of a 3500 m^3 globe for post-smolts of Atlantic salmon. The results of turbulence model of the pilot globe were validated against the velocity measurements using acoustic Doppler velocimetry. Computational assessment of various flow characteristics includes the velocity and vorticity fields. The streamline pattern confirmed the secondary vortices, creating the tea-cup hydrodynamics. Coherent vortices, identified by means of Q-criterion, show the presence of vortex column in the globe. Two inlet configurations were tested on the post-smolt globe for improved performance. Design 1 has the standard one-column nozzle configuration, and the Design 2 has two-column nozzles to create a V-shaped inflow. The mixing action of the two designs was examined using Lagrangian particle tracking. Considerable influence of inlet configuration on the particle motion was observed. It was found that V-nozzles (two columns of inlet nozzles) are more effective than standard nozzles in flushing the solid particles.

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Nomenclature

A	Area
C_1, C_2, C_μ, $C_{1\varepsilon}$	Model constants of Realisable $k-\varepsilon$ model
C_D	Particle drag coefficient
C_p	Model constant of eddy interaction model
d	Particle diameter
f	Force
g	Gravitational constant
k	Turbulent kinetic energy
ℓ	Turbulence length scale
m	Particle mass
p	Pressure
P_k	Production term of turbulent kinetic energy
R	Reynolds stress tensor
Re	Reynolds number
S_{ij}	Strain rate tensor
Stk	Stokes number
T_L	Integral time scale of turbulence
T_P	Particle time to traverse the eddy
v	Velocity
v'	Fluctuating component of velocity
$\overline{v}$	Average velocity
$\overline{\mathrm{v}}$	Velocity vector
v_p	Particle velocity
$y+$	Non-dimensional wall distance

Greek symbols

γ	Flow uniformity index
δ	Kronecker Delta
ε	Dissipation rate of turbulent kinetic energy
ι	Turbulence intensity
μ	Statistical mean
μ_d	Dynamic viscosity
μ_t	Turbulent viscosity
ν	Kinematic viscosity
ρ	Water density
ρ_p	Particle density
σ	Standard deviation
τ	Stress tensor
τ_w	Wall shear stress
ϑ	Particle volume
Ω	Rotation tensor

Abbreviations

ADV	Acoustic Doppler Velocimetry
CAD	Computer Aided Design
CCS	Closed containment system
CFD	Computational Fluid Dynamics
CV	Coefficient of variation
DNS	Direct numerical simulation
EIM	Eddy interaction model
IGES/IGS	Initial Graphics Exchange Specification
MPI	Message passing interface
SIMPLE	Semi-implicit method for pressure linked equations
SNR	Signal-to-noise ratio
STEP/STP	Standard for the Exchange of Product data
STL	Stereo-Lithography
URANS	Unsteady Reynolds Averaged Navier-Stokes
WSS	Wall shear stress

1. Introduction

The production of Atlantic salmon is the paramount activity in Norwegian aquaculture, accounting for more than 80% of the total aquaculture production in the country. With a thousand-fold growth over last four decades, Norway is currently contributing more than one third of the global salmon production. Aspiring to increase the salmon production by five times by 2050, Norwegian aquaculture has been evolving with new businesses and innovative technologies with a focus on the environmental performance of fish farms (Hagspiel, Hannevik, Lavrutich, Naustdal, & Struksnæs, 2018; Olafsen, Winther, Olsen, & Skjermo, 2012). However, there are many challenges facing this proposed five-fold expansion in production, which include sea lice, diseases, production losses etc. This necessitates innovative production systems such as closed-containment systems (CCS), where the fish are separated from the outside environment. With a better control on production, environmental impact and disease transmission makes CCS a promising alternative to open-cage production systems.

There has been a growing interest in the Norwegian aquaculture industry in CCS solutions for post-smolts (Hagspiel et al., 2018; Summerfelt, Mathisen, Holan, & Terjesen, 2016). Post-smolts are salmon being adapted to sea water life, and up to about 1 kg. Although the harvest size is about 5 kg, the post-smolt stage still amounts to approximately half the production time cycle in the sea due to the growth characteristics of salmon. By keeping the post-smolts in closed systems, this considerably reduces their exposure to sea lice, and also these systems are a more stable environment for fish production. At 4% annual growth, production in Norway should increase to 3,000,000 t by 2030. Thus, CCS plants by 2030 can be expected to account for a production of 500,000 t. The industry is therefore interested in innovative solutions to achieve this.

Little research has been done to investigate flow hydrodynamics in CCS using computational methods. However, the subject of rotational flows in confined domains has been investigated for some time, but in different applications. For instance, the early experimental studies of Willingham, Sedlak, Rossini, and Westhaver (1947), and Macleod and Matterson (1959) considered the flow behaviour in the rotary fractionation columns. Kloosterziel and van Heijst (1991) performed experiments to analyse the vortices in a rotating fluid. The study noted several observations on vortex stability, which imply that the characteristics of rotating fluid largely