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Intrinsic settling rate and spatial diffusion properties of extruded fish feed pellets

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ABSTRACT

Spatial and temporal feed distribution in sea cages are important factors for the farmer, fish and environment due to the strong relation to growth, feed loss, pollution and welfare. This study presents a set of experimentally derived diffusion parameters and settling rates obtained in still water from four sizes and three densities of extruded fish feed pellets commonly used in aquaculture. It was found that pellet size is positively correlated with increased diffusion and that pellet density plays a less important role. Both the size and density of pellets had a significant impact on the settling rate. Results are compared to values obtained during feed production as well as other relevant studies. The findings suggest that parameters related to hydrodynamic behaviour of groups of feed pellets may vary across different pellet types. The results may be applied to refine and parameterize pellet motion in sea cage feeding models, improving estimates of fish behaviour, growth and feed loss.

1. Introduction

Salmon (*Salmo salar*) farming is rapidly expanding across the world with global production of just 297 tonnes in 1970 compared to over 2,087,000 tonnes in 2013 (FAO, 2015). Production has moved from moderately sized cages owned by small companies to a consolidated industry with large production sites over the last decades. Cages are usually rectangular with 20–40 m sides and 20–35 m depth, or circular with a circumference of 90–157 m up to 48 m depth (Oppedal et al., 2011). In Norway, a single cage may hold up to 200,000 fish yielding a biomass of 1000 tonnes at an typical average slaughter weight of 5 kg. A daily feed ration of 1% (Oehme et al., 2012) corresponds to 10 tons of feed per cage per day. The expenditure on feed amounts to roughly 50% of all costs in Norwegian salmon and trout farming (Norwegian Directorate of Fisheries, 2013). With the feed loss from commercial farms estimated to around 7% (Gjøsæter et al., 2008), wasted feed is a substantial economic loss for the farmer as well as poor utilization of marine and plant resources (Alfredsen et al., 2007). Feed loss may in addition have a negative impact on the surrounding marine environment. Wild fish are drawn close to the cage enabling transmission of diseases between farm sites (Dempster et al., 2009) and large amounts of wasted feed in their diet can cause changes in their filet quality (Fernandez-Jover et al., 2007).

Feed waste is one concern, but the spatiotemporal distribution of pellets within the cage is also an important parameter for the fish. Giving easy feed access for the fish by utilizing the cage volume is desirable and is likely to promote rapid growth. The spatial and temporal distribution of pellets and ration size are key factors concerning feed availability (Juell, 1995) and these factors should not be confined so the fish may forage in an unrestricted manner (Talbot et al., 1999). The spatial distribution of pellets has a considerable influence on equal feed access (Attia et al., 2012) and localized feed delivery permits resource monopolization by dominant or competitive individuals, restricting feed access to subordinates (Juell, 1995; Ryer and Olla, 1996) causing greater size variation across the population (Johansen and Jobling, 1998). Suboptimal feed intake leads to both reduced and inefficient growth in Atlantic salmon (Einen et al., 1999). Aggressive behaviour and fin damage related to feed access have been demonstrated in a range of Salmonidae (Brännäs et al., 2005; Fenderson et al., 1968; Jobling, 1985; Noble et al., 2007, 2007, 2008; Rasmussen et al., 2007; Symons, 1971; Talbot et al., 1999) and summarized by Attia et al. (2012), Ruzzante

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(1994) and Talbot (1993), and this aggression is in turn related to injuries and mortality (López-Olmeda et al., 2012). Optimizing the spatiotemporal pellet distribution could thus result in considerable economic, environmental and welfare benefits.

To achieve these goals more knowledge must be obtained on the interaction between the feed, fish and the environment, on which models may be created to enable simulation and optimization of feed delivery.

In Norwegian salmon farming, feed is presented to the fish in the form of cylindrical pellets where the diameter is adapted to the size of the fish, normally from 3 to 12 mm diameter (Skretting, 2012) during the ongrowth in the sea. Feed pellets are commonly produced using an extrusion process. The extrusion system has a preconditioner which mixes water and steam into the dry ingredients in order to obtain a uniformly moisturized and preheated mix for the extruder barrel (Sørensen, 2012). This barrel housing may contain one or two rotating screws which mixes and transports the feed. The heated mix obtains its final pellet shape by being forced through a die plate and cut to length by a rotating knife (Sørensen, 2012). The pellets are dried and oil is finally added to increase the energetic content and obtain the desired density of the pellets. On farms feed is conveyed from large silos onboard a barge using compressed air to propel pellets through a pipe to a rotary pneumatic spreader located on the surface in the centre of the sea cage. Pellet transport, spreader rotation and pellet throw is driven by the same airflow.

For reference, the term settling rate refers to the intrinsic sinking speed of pellets, diffusion describes how random motion causes pellets on average to move from an area of high concentration to low concentration and advection is the motion of pellets caused by the bulk motion of the surrounding water. Above surface, Oehme et al. (2012) performed the first experiment which characterized the spatial pellet distribution from a rotary spreader by collecting pellets in Styrofoam boxes on the surface. Numerical models of the spreader have also been derived to investigate effects of different designs and wind (Skoien et al., 2015, 2016). For the pellet distribution below the surface an initial numerical model was developed by Alver et al. (2004) and has since been extended with a fish behaviour and foraging model (Føre et al., 2009). The combined model has been further developed and takes into account a range of factors such as the pellet distribution pattern across the surface, pellet size and settling rate, feeding rate, water flow and temperature. It also accounts for the fish properties with respect to motion, biomass and size distribution, appetite/satiation, foraging pattern and behaviour (Alver et al., 2016).

In Alver et al. (2004, 2016) the pellet concentration of a sea cage was modelled using the transport equation to describe the spatiotemporal dynamics of its distribution.

$$\frac{\partial c}{\partial t} + v_x \frac{\partial c}{\partial x} + v_y \frac{\partial c}{\partial y} + (v_z + u_v)\frac{\partial c}{\partial z} + \kappa \left(\frac{\partial^2}{\partial^2 x} c + \frac{\partial^2}{\partial^2 y} c + \frac{\partial^2}{\partial^2 z} c \right) = u - f_I \tag{1}$$

According to Alver et al. (2016), $c(x, y, z, t)$ is the feed concentration in the coordinate system given by the horizontal plane x, y, the vertical axis z and time respectively. $v_x(x, y, z, t)$, $v_y(x, y, z, t)$ and $v_z(x, y, z, t)$ are the individual orthogonal components of the water flow, u_v is the settling rate of the pellets, κ is the diffusion factor, $u(x, y, z, t)$ is the added feed and $f_I(x, y, z, t)$ the ingestion rate of the fish at a given position and time. In the present experiments, there is no water flow or fish. Eq. (1) can thus be simplified to Eq. (2).

$$\frac{\partial c}{\partial t} + u_v \frac{\partial c}{\partial z} + \kappa \left(\frac{\partial^2}{\partial^2 x} c + \frac{\partial^2}{\partial^2 y} c + \frac{\partial^2}{\partial^2 z} c \right) = u \tag{2}$$

It is not the intention of the present study to give a detailed account of the model as a comprehensive description can be obtained from Alver et al. (2004, 2016). Both κ and u_v which are parameters of essential importance have been determined based on the findings in the current study.

Limited research has been conducted with regards to characterizing the intrinsic diffusion properties of extruded fish feed pellets. This results in a range of sea cage and deposition models such as (Alver et al., 2004; Cromey et al., 2002, 2009; Gillibrand and Turrell, 1997) being based on alternative data as opposed to experimentally derived parameters from representative feeds. There has, however, been performed extensive research in determining the vertical settling rate u_v for various fish feeds (Chen et al., 1999; Cromey et al., 2002, 2009; Findlay and Watling, 1994; Sutherland et al., 2006). There may be several factors and interactions influencing diffusion. Heavier pellets may diffuse less simply because they will be suspended in the water column for a shorter period of time compared to a lighter pellet. However, a stronger relationship may be governed by a relation between size and increased diffusion due to greater settling rate and thus a higher level of erratic motion. It is also likely that density as well as size affects the settling rate due to the non-linear relationship between surface area/mass across different sized pellets.

The contribution of this study is a description of the pellet settling rate and diffusion process obtained through experiments involving a range of pellet types with different characteristics. These results may be of importance in determining central parameters in any feeding model involving pellets. The horizontal diffusion and vertical settling rate characteristics have been derived from the same pellets giving added benefit of matched data describing the motion of a pellet along all three axes. The results have been applied to the model described by Alver et al. (2016) to improve the estimation of the spatial and temporal pellet distribution.

2. Materials and methods

The work described in this study has been conducted as two separate experiments denoted the diffusion experiment and the settling rate experiment. The former quantifies the natural diffusion of pellets in the horizontal x, y plane released from a single point until they settle on the bottom. The latter is an extensive investigation of the settling rate and the vertical (z-axis) distribution of pellets dropped from an altitude, similar to being distributed by a rotary spreader. The diffusion and settling rate experiment are described in Sections 2.2 and 2.3 respectively.

2.1. Pellet properties

The experimental pellet types were produced at Nofima Feed Technology Centre, Bergen, Norway. Four different pellet sizes of {3, 6, 9, 12} mm diameter and cylindrical shape were produced to cover a wide range commonly used in Atlantic salmon farming. Each of the four pellet sizes were coated with three different amounts of oil to obtain pellets of low, medium and high density $\{L, M, H\}$, giving a total of twelve different pellet types. Each type is denoted by its pellet size and density, e.g. *9M* denotes a 9 mm pellet of medium density. The diet formulation was similar to the average Norwegian salmon feed in 2010 (Ytrestøyl et al., 2011). One basal mix of the dry feed ingredients was made and divided into four batches prior to extrusion. The four batches were processed with similar conditions in a Wenger TX52 extruder (Wenger, KS, USA), but with die plate holes of 2.5, 4.5, 7.2 and 10.0 mm diameter. The cutting knife speed was, however, adjusted for each production to ensure pellets with a length:diameter ratio of approximately 1:1. The pellets were dried to 92% dry matter in a hot air dual layer carousel dryer (Paul