

# A MODEL FOR THE SETTLING VELOCITY OF FLOCS; APPLICATION TO AN AQUACULTURE RECIRCULATION TANK

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## ABSTRACT

A general model for flocs settling velocity is still an open field of research in the scientific literature. In this work, a reduced model of an aquaculture recirculation tank was used to validate a model for floc settling velocity. Cohesive sediments from non-used food and fish excreta are a main concern in those tanks design. Excess concentrations of sediments can cause fish death or additional costs of energy for aeration. This research is aimed to understand the settling behavior of flocs when subjected to a liquid shear rate. A reduced scale model of an aquaculture recirculation tank was built in Plexiglas in order to use particle image velocimetry and particle tracking velocimetry techniques to measure fluid velocities, solid settling velocities, flocs shape and size.

Different flow rates and solid concentrations were used to develop varied configurations in the system; models for floc settling velocity based on fractal theory were calibrated. Cohesive sediments from fish food were observed in long-term experiments at constant fluid shear rate in the recirculation tank. A group of 50 images were obtained for every 5 min. Image analysis provided us with floc settling velocity data and floc size. Using floc settling velocity data, floc density was obtained for different diameters at equilibrium conditions, after 1 h or larger experiments. Statistical analysis of floc velocities for different floc sizes allowed us to obtain an expression for the drag coefficient as a function of floc particle Reynolds number ( $R_{ep}$ ). The results were compared with floc settling velocity results from different researchers. The model is able to define the general behavior of floc settling velocity, which shows a reduction for larger flocs that is not taken into account in classical models. Only two parameters of the drag coefficient model for a permeable spherical particle are needed to be calibrated, for different types of sediments, in order to have more general applicability.

*Keywords:* Aquaculture, drag coefficient, flocs, flocs density, fractal dimension, permeable particle, PIV, PTV, recirculation tank, settling velocity.

## 1 INTRODUCTION

The settling velocity of cohesive sediments is an important design parameter in aquatic environments such as water treatment installations, storm water ponds, sediment filling in lakes, sedimentation in estuaries, dredging in rivers and sediment removal in aquaculture devices especially when water scarcity is a concern [1]. The reuse of water is the main characteristic of the latter systems.

The efficient solids removal is a main concern in these systems because of the accumulation of non-used food and fish excreta. These solids are generally  $<65 \mu\text{m}$  in diameter and behave as cohesive sediments [2]. These sediments form flocs or aggregates, made of water, inorganic particles and organic particles [3–5]. To obtain adequate settling models for these particles is an open field of research [6].

The most used tanks are circular [7,8]. Water is supplied in these tanks by means of diffusers at the walls. In this work, a small-scale circular water recirculation tank was used in order to study the solids behavior in the tank. There is a central settling device in order to remove the solids (Fig. 1). The settling device functions according to the hydro cyclones principle [9].

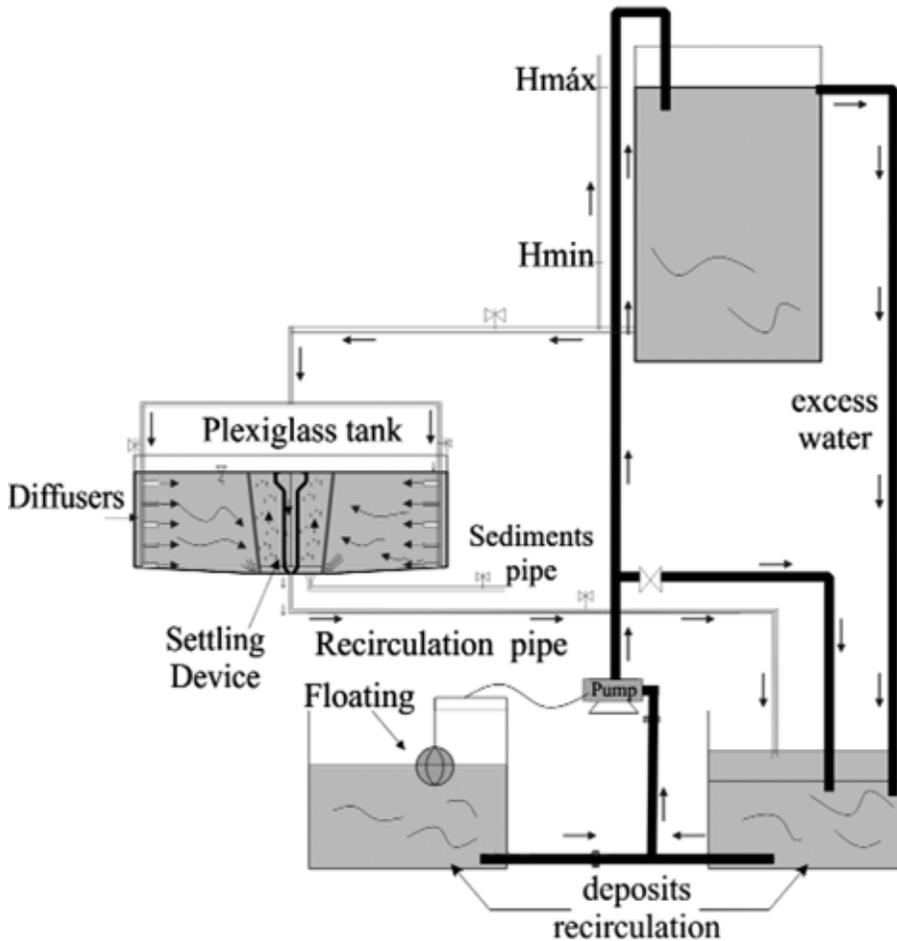


Figure 1: Small-scale water recirculation tank.

Two optical techniques were used in this work, particle image velocimetry (PIV) to measure fluid velocities and particle tracking velocimetry (PTV) [10] to measure particle velocities. Polyamide tracers  $5\ \mu\text{m}$  in diameter were used to obtain fluid velocities using PIV, and flocs were used as tracers in the PTV technique. PTV also allowed us to measure particle size and shape. Scanning electron microscopy (SEM) was also used to define size and shape of primary particles.

The attempts to model settling velocity as a function of floc size, shape and density demonstrated that density varies with floc size [10]. Later work demonstrated that floc density depends on the fractal nature of flocs [11]. Recently, the effect of shear rate on floc density was demonstrated by Garcia-Aragon *et al.* [12].

In this research, the results were used to calibrate settling velocity models using fractal theory, including an adequate definition of the drag coefficient for permeable flocs. Experimental data of cohesive sediments available in the scientific literature [13–16] were compared with the model developed in this research. The proposed model is shown to be able to reproduce these results if a calibration of the parameters defining the drag coefficient for permeable particles is properly done.

## 2 EXPERIMENTAL SET-UP

A small-scale water recirculation tank made of plexiglass 1.03-m diameter and 35-cm depth was used in the experiments. A complete system for water recirculation (Fig. 1) was implemented; diffusers at the wall control the flow rate and tank water velocity. The circular flow is generated by diffusers at different levels in the tank wall; water is obtained by a high rise tank with a constant water level in order to supply a constant flow rate by gravity. A settling device in the center of the tank allows solids removal. The sediments used were common food for fishes. A preprocessing (screening in a 200 mesh) was needed in order to obtain sizes <65 μm.

For the PIV and PTV techniques, a 15-mJ Nd:YAG laser with double cavity (double pulsed) was used. Two CCD cameras, one LUMENERA with 60 fps and resolution 640 × 480 pixels and the other JAI with 250 fps and 1600 × 1400 pixels were used. Both cameras were equipped with 50-mm NIKON lenses. For synchronization, a NI-PCIE-1430 card was used.

## 3 METHODS

The main difficulty for the proposal of a settling velocity model for flocs is the adequate definition of their density. Many models have been formulated for floc density, the more accepted for spherical flocs composed of spherical primary particles is the one proposed by Kranenburg [17] (eqn 1):

$$\rho_f - \rho_w = (\rho_p - \rho_w) \left( \frac{D}{d} \right)^{F-3} \tag{1}$$

where  $\rho_f$ ,  $\rho_w$ , and  $\rho_p$  are the densities of floc, water and primary particles,  $D$  is the floc diameter and  $d$  is the primary particles diameter.  $F$  is the fractal dimension and the model assumes that the floc is constituted of spherical primary particles of equal diameter. The primary particles aggregate by physico-chemical mechanisms in order to constitute the floc. The model can be used for non-spherical particles with equivalent diameters, but in this case the calculation of the fractal dimension becomes difficult.

To overcome this difficulty in this research, we used a different model to fit the experimental data, and then we compared both models and were able to obtain the fractal dimension of the experimental flocs. The floc density model used was that of Lau and Krishnappan [18] (eqn 2):

$$\rho_f - \rho_w = (\rho_p - \rho_w) \exp(-bD^c) \tag{2}$$

where the parameters  $b$  and  $c$  depend on floc type and shear rate applied [6].

The appropriate values of  $b$  and  $c$  were obtained with the experimental settling velocity of the sediments used (fish food), when plotted against floc diameter. The best fit to a modified Stokes equation using eqn (2) was performed. Comparing eqns (1) and (2), a relationship for the fractal dimension  $F$  is obtained:

$$F = 3 - \frac{bD^c}{\ln\left(\frac{D}{d}\right)} \tag{3}$$

The fractal dimension is a measure of floc compactness. The values of  $F$  near 3 signify a near rigid body and below 2 an aggregate with high porosity.

A balance of drag forces and gravitational forces gives the following equation:

$$W_s^2 = \frac{4(\rho_f - \rho_w)gD}{3C_{Df}\rho_w} \tag{4}$$

where  $W_s$  is the floc settling velocity and  $C_{Df}$  is the permeable particle drag coefficient. Using eqn (1), the following relationship for the settling velocity is obtained:

$$W_s = \sqrt{\frac{4(S-1)g(D)^{F-2}}{3C_{Df}(d)^{F-3}}} \tag{5}$$

where  $S$  is the primary particles relative density.

To define the drag coefficient in a permeable floc, the results of Rojak and Flagan [19] were used for the permeability factor  $\xi$  of a spherical particle; they propose the following equation:

$$\xi^{-2} = \left[ 1 - \gamma \left( \frac{d}{D} \right)^{3-F} \right] \left( \frac{\left( \frac{d}{D} \right)^{2F-6}}{\gamma^2} - \frac{2 \left( \frac{d}{D} \right)^{F-3}}{\gamma} + 1 \right) \frac{\left( \frac{d}{D} \right)^2}{45} \tag{6}$$

The permeability factor of the spherical particle is a dimensionless parameter. It is related to the more known permeability  $\kappa(m^2)$  in the following way;  $\xi = D/2\kappa^{1/2}$  [20], where  $\gamma$  is the compaction factor of the floc and refers to the kind of arrangement between the primary particles. A value near 1 means close packed particles (elongated) and  $\gamma$  is dimensionless. From Neale *et al.* [21], a relationship between the drag coefficient of a permeable spherical particle and an impermeable one ( $\Omega$ ) is obtained. Abade *et al.* [22] propose the following equation for the dimensionless factor  $\Omega$ :

$$\Omega = \frac{2\xi^2 \left( 1 - \frac{\tanh \xi}{\xi} \right)}{2\xi^2 + 3 \left( 1 - \frac{\tanh \xi}{\xi} \right)} \tag{7}$$

Assuming that the drag coefficient of the impermeable sphere is  $C_D=24/Re_p$ , where  $Re_p=W_s D/\nu$  and  $\nu$  is the kinematic viscosity of water. Using eqns (6) and (7), a value of  $C_{Df}$  could be obtained with the relationship  $C_{Df} = \Omega C_D$ .

#### 4 RESULTS

Figures 2–4 show PTV experimental results of settling velocities versus diameter at different times during a 40-min experiment. The solid line represents the best fit to a modified Stokes equation that takes into account eqn (2).

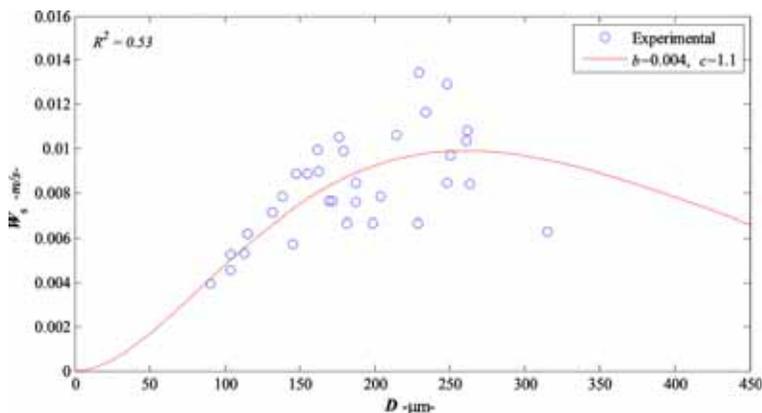


Figure 2: Settling velocities and best fit curve for  $t = 10$  min.

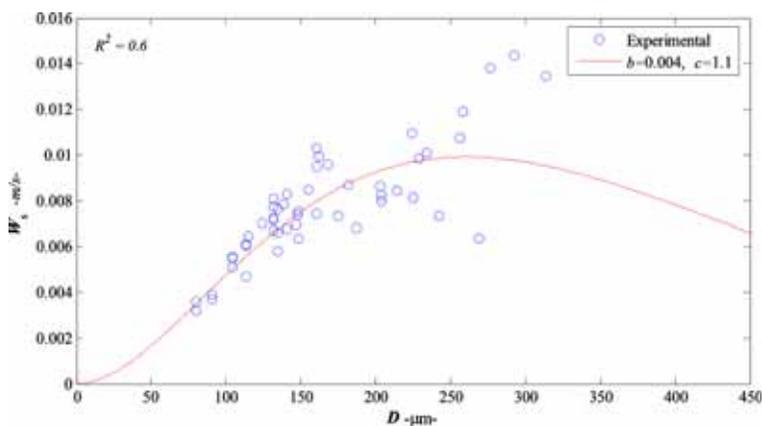


Figure 3: Settling velocities and best fit curve for  $t = 20$  min.

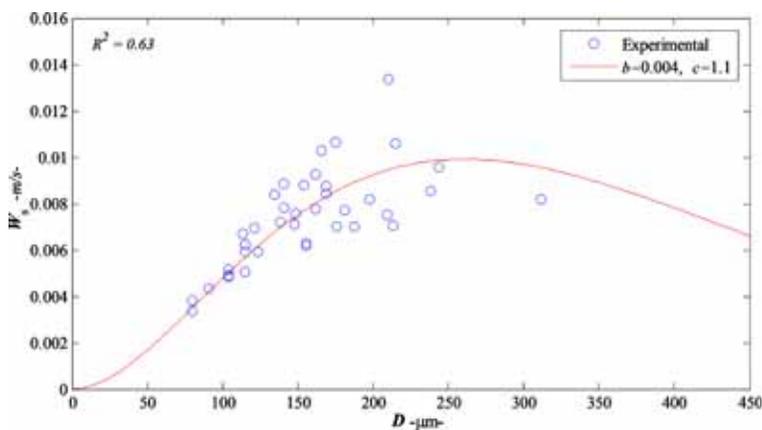


Figure 4: Settling velocities and best fit curve for  $t = 30$  min.

For all the experimental results, the best fit curve was obtained with the values of  $b = 0.004$  and  $c = 1.1$  in eqn (2).

With these values of  $b$  and  $c$ , using eqn (3), the variation of  $F$  with  $D$  is obtained (Fig. 5).

With the relationship between fractal dimension and diameter, the values of permeability can be obtained for different floc diameters, using eqn (6). A mean value of  $20 \mu\text{m}$  was obtained from SEM (Fig. 6), for primary particle diameters. Also by means of SEM observations, the value of  $\gamma$  was defined as 0.6, because most of the primary particles are almost spherical. The drag coefficient for the floc  $C_{DF} = \Omega C_D$  is obtained using eqn (7).

Plotting  $C_{DF}$  against  $R_{ep}$ , Fig. 7 is obtained.

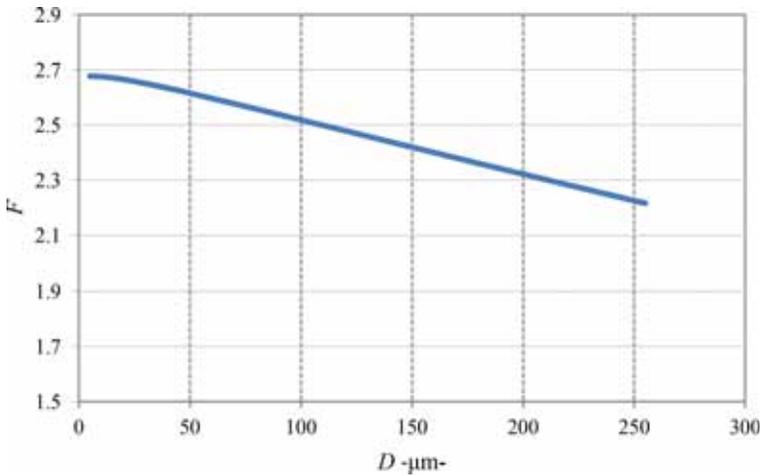


Figure 5: Fractal dimension versus diameter.

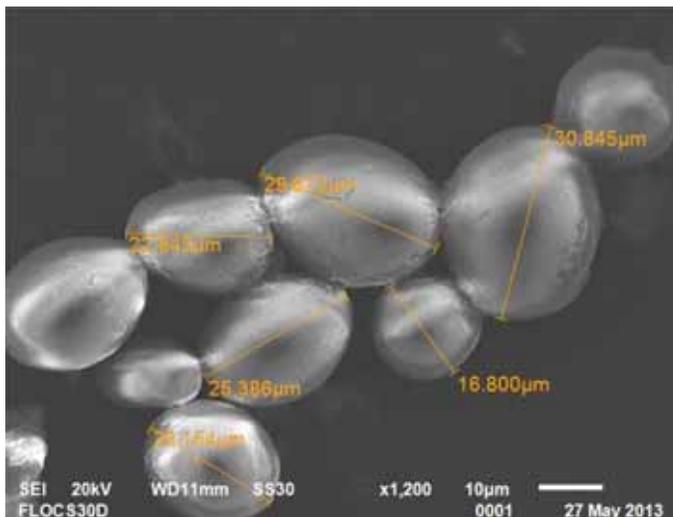


Figure 6: Representative floc captured with SEM.

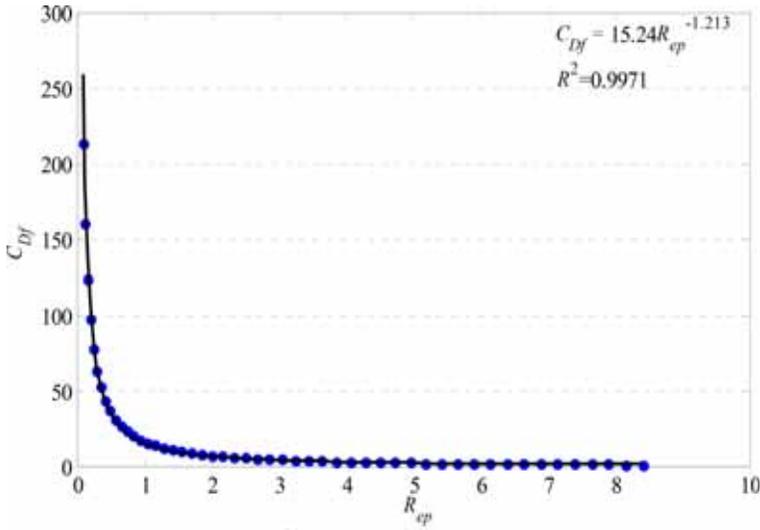


Figure 7: Drag coefficient versus particle Reynolds number.

A relationship between the drag coefficient and the particle Reynolds number was obtained by cross-correlation (eqn 8)

$$C_{Df} = \frac{15.24}{R_{ep}^{1.21}} \tag{8}$$

The equation for the permeable drag has the form  $C_{Df} = a/R_{ep}^n$ . Where  $a$  and  $n$  are constants depending on the kind of cohesive sediments and should be experimentally calibrated.

If we replace this relationship in eqn (5), the following relationship for the settling velocity is obtained:

$$W_s = \frac{[13.08(S - 1)]^{\frac{1}{2-n}} D^{\frac{F+n-2}{2-n}}}{a^{\frac{1}{2-n}} v^{\frac{n}{2-n}} d^{\frac{F-3}{2-n}}} \tag{9}$$

Using eqn (9) with  $a = 15.24$  and  $n = 1.21$  and considering  $v = 1e6 \text{ m}^2/\text{s}$ , the following equation for the settling velocity for food fish was obtained [23]:

$$W_s = \frac{1.275e9 \cdot (S - 1)^{1.266} D^{1.266F-1}}{d^{1.266F-3.797}} \tag{10}$$

where  $W_s$  is in m/s and  $D$  and  $d$  in m.

The results show that the drag coefficient of a permeable particle is reduced compared with an impermeable particle of the same diameter as previously stated by Johnson *et al.* [24].

In order to show the usefulness of eqn (9), a summary of floc settling velocities from the scientific literature summarized by Khelifa and Hill [16] were plotted in log-log paper. It is shown that eqn (9) is able to reproduce the general trend (Fig. 8), increasing velocities with increase in diameter until diameters around 400  $\mu\text{m}$  and then decreasing velocities for larger diameters.

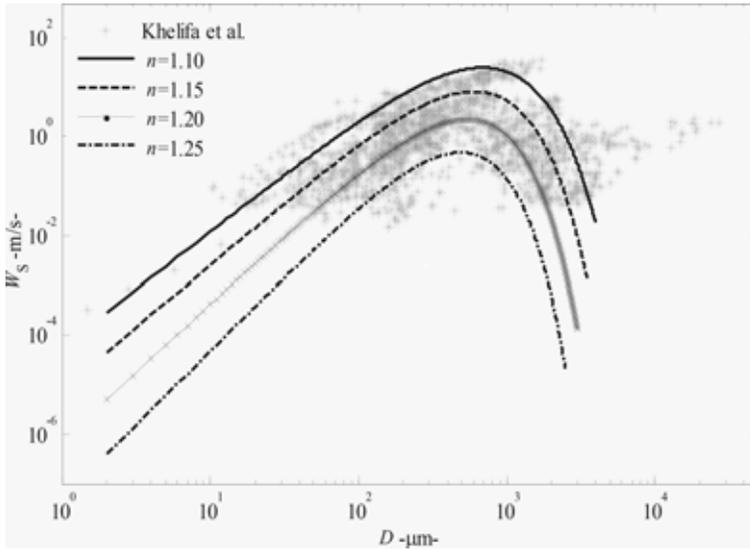


Figure 8: Settling velocity versus diameter, variation with  $n$ .

Figure 8 shows the measured settling velocities of different authors. The value of  $a = 15$  was kept constant. According to eqn (3), the value of  $F$  varies with  $n$  and  $a$  following eqn (11):

$$F = 3 - \frac{\left(\frac{1}{a}\right)^{2n} D \left(n - \left(\frac{1}{a}\right)^{0.85n}\right)}{\text{Ln}\left(\frac{D}{d}\right)} \tag{11}$$

Because of data dispersion, due to the heterogeneity of cohesive sediments represented, going from rivers, estuaries to waste water flocs, it was necessary to vary  $n$  between 1.1 and 1.25. It was shown that if a proper calibration of the drag coefficient parameters  $a$  and  $n$  is done, eqn (9) is able to reproduce settling velocities for an ample kind of sediments. Of course, the fractal dimension is affected by these parameters according to eqn (11). Figure 9 shows the variation of fractal dimension with floc diameter for the parameters  $a = 15$  and  $n$  used in this research.

### 5 CONCLUSIONS

A model for flocs settling velocity was developed. The model depends on the parameters of a drag coefficient for permeable particles. Using optical techniques for flocs from fish food cohesive sediments in a small-scale water recirculation tank, it was possible to define an appropriate settling model. The experimental results allowed us to obtain appropriate parameters for a floc density versus diameter model. Using this model, the fractal dimension variation with diameter was obtained. With a balance of gravitational forces and drag forces, a model for flocs settling velocity was developed. This model contains one undefined parameter, the permeable floc drag coefficient.

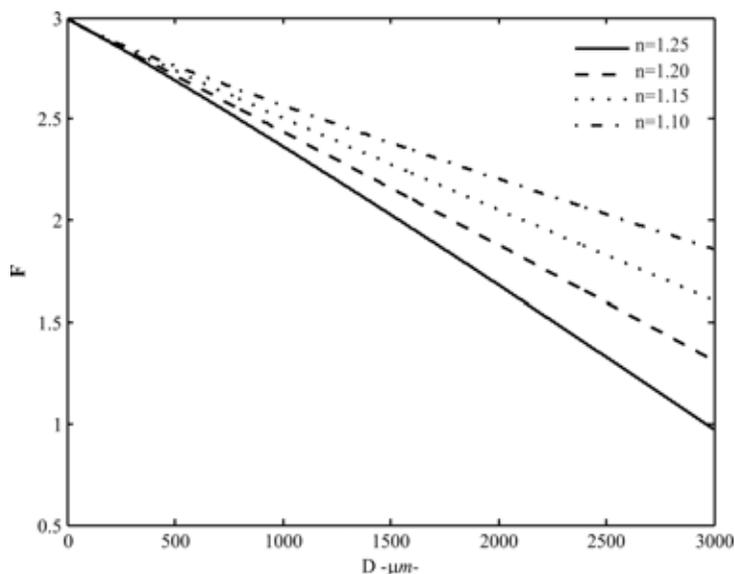


Figure 9: Variation of  $F$  with  $n$ .

Using some relationships between permeable spherical particles and non-permeable spheres and the experimental results, an appropriate definition of the drag coefficient for fish food was obtained.

The settling velocity model is able to reproduce results from a great variety of types of flocs. It was used with settling velocity data for different kinds of cohesive sediments, and it was able to reproduce the main trends observed. To use the model, a previous step of calibration needed is that of the drag coefficient parameters  $a$  and  $n$ . The model could be very helpful for the prediction of settling velocities and used to improve waste water treatment facilities, sedimentation behavior in natural watercourses and in the design of solids removal devices in aquaculture water recirculation tanks.

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