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Settling velocities of multifractal flocs formed in chemical coagulation process

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ABSTRACT

A number of different flocculation mechanisms are involved in the formation of chemical coagulation flocs. Consequently, two flocs with the same size may have been formed by different mechanisms of aggregation and therefore have different arrangement of primary particles. As a result, two flocs with the same size may have different masses or mass distributions and therefore, different settling velocities. Although the correct estimation of the floc mass and density is critical for the development of the floc settling model, none of the suggested floc settling models incorporate the information on mass distribution and variable density of flocs. A probability-based method is used to determine the floc fractal dimensions on floc images. The results demonstrated that flocs formed in lime softening coagulation are multifractal. The multifractal spectra indicated the existence of a multiple fractal dimensions as opposed to the unique box-counting dimension which is a morphology-based fractal dimensions typically introduced into the Stokes' Law. These fractal dimensions may provide information on the flocs' aggregation mechanism, floc's structure, and the distribution of mass inside the floc. More research is required to investigate how to utilize the information obtained from the multifractal spectra to incorporate the variable floc density and nonhomogeneous mass distribution of flocs into the floc settling models.

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1. Introduction

In the past three decades, numerous attempts have been undertaken to incorporate floc fractal dimensions into the models describing their settling velocity (Tambo and Watanabe, 1979; Li and Ganczarczyk, 1989; Lee et al., 1996; Winterwerp, 1998; Logan 1999; Kim, 2001; Li and Yuan, 2002; Chung and Lee, 2003; Khelifa and Hill, 2006; Yang et al., 2008; Vahedi and Gorczyca, 2011; Maggi, 2013).

In this paper, the floc settling models and the assumptions used in their development are critically analyzed. Also a probability-based approach is used to investigate whether flocs formed in lime softening process are multifractals, i.e. their properties have to be characterized by multiple scaling relationships. Advanced analyses of projections of floc images are conducted to obtain multifractal spectra that provide information on other fractal dimensions that may be useful in characterizing these flocs.

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List of symbols

v_s	Floc settling velocity, m.s^{-1}
V_f	Floc volume, m^3
V_p	Primary particle volume, m^3
ρ_f	Floc density, kg.m^{-3}
ρ_p	Density of the primary particles, kg.m^{-3}
μ	Dynamic viscosity, kg.m^{-1}.s^{-1}
d	Particle (floc) size, m
d_p	Primary particle size, m
d_{50}	Median size of the component particles within floc, m
C_d	Drag coefficient
Re	Particle Reynolds number
A_f	Cross-sectional area of the floc projection, m^2
D_f	Mass fractal dimension of the floc
D_p	Mass fractal dimension of the primary particles
D_q	Rényi dimension
M_f	Floc mass, kg
m	Mass of a primary particle
N	The number of primary particles within a floc
P_{rj}	Probability that the floc area is contained inside the measurement pixel (r)
α_q	Singularity strength
f_q	Singularity spectrum

2. A review of development of the flocs settling velocity equations

In this section, the assumptions used for development of floc settling models that incorporate fractal dimensions of flocs are critically reviewed. All models developed to describe the settling of aggregates (flocs) are based on Stokes' Law, which is derived from the force balance on an individual floc settling at the terminal velocity, v_{st}. The gravitational force reduced by the buoyancy acting on a floc is given by:

$$F_g - F_b = (M_f - M_w)g = \left(V_f\rho_f - V_f\rho_w\right)g = V_f\left(\rho_f - \rho_w\right)g \quad (1)$$

where, V_f is the floc volume, ρ_f and ρ_w are densities of the floc and water respectively, g is the gravitational acceleration, M_f is the total mass of the aggregate and M_f is the equivalent mass of water occupying the floc volume.

At the terminal velocity, the effective gravity force is equal to the drag force acting on the floc

$$F_d = C_d\frac{1}{2}A_f\rho_w v_{st}^2 \quad (2)$$

where, C_d is drag coefficient, A_f is the floc's cross-sectional surface area and v_{st} is the terminal settling velocity of the floc.

2.1. Estimation of the mass and volume of flocs

Eq. 1 and Eq. (2) require information on floc's volume, floc's density and floc's cross-sectional area. In all of the reviewed studies, the floc's mass or volume are determined assuming that the total mass or volume of the aggregate can be computed by adding up masses or volumes of all primary particles composing the aggregate:

$$M_f = V_f\rho_f = Nm = NV_p\cdot\rho_p \quad (3)$$

where, ρ_p and V_p are the density and volume of the primary particles forming the floc, N is the number of primary particles, and m is the mass of a primary particle.

An important assumption in Eq. (3) is that all primary particles have the same mass. This is incorrect for aggregates formed in water and wastewater which are composed of a variety of particles of different sizes. All of the reviewed studies use the assumption in Eq. (3) to rewrite Eq. (1) as:

$$V_f\left(\rho_f - \rho_w\right) = N\cdot V_p\left(\rho_p - \rho_w\right) \quad (4)$$

It is important to note that, analogically to the floc mass, the floc volume in Eq. (4) is computed by adding up the volumes of primary particles only. The flocs contain significant amounts of chemical coagulant species and/or microbial by-products such as extracellular polymers. Both the coagulant and the extracellular polymers have very low densities, therefore, their contribution to the total mass of the aggregate may be small but they can occupy a significant part of the floc volume and create low density regions within the floc. Therefore, computing the floc mass by adding volumes of the primary particles alone totally ignores the presence of the hydrolyzed coagulant species. In summary, the mass and volume of a floc formed in chemical coagulation cannot be computed by adding up the masses or volumes of primary particles alone.

2.2. Floc density and floc aggregation mechanisms

All equations presented so far assume constant density of the primary particle (ρ_p). As mentioned before, flocs in water treatment are aggregates of a variety of different primary particles that not only have different sizes but also have very different densities. For instance, the density of calcium carbonate primary particles is about 2700 kg/m^3 (Vahedi and Gorczyca, 2011), whereas the primary particles of coagulant hydrolysis products have densities very close to the water density, i.e. about 1000 kg/m^3.

These different primary particles with different densities aggregate into flocculi, which assemble themselves into microflocs. Microflocs bind together to form floc aggregates. Therefore, the floccule is a "primary particle" for microflocs and microflocs are the primary particles for floc aggregates. The important feature of flocs formed in chemical coagulation is that each level of floc aggregation (floccli, microflocs, floc aggregate) may be formed according to a different mechanism. Therefore, different primary particles arrangements may be present inside the floccule, the microfloc or the floc aggregate. The consequence of these complex aggregation mechanisms is that the densities of the floccule, the microfloc and the floc aggregate will be different (Gorczyca and Ganczarczyk, 2002). This mechanism of floc formation results in a floc with a multilevel structure and a nonhomogeneous density (mass distribution).

Eq. 4 requires an estimation of the number of primary particles forming the floc, N. The following equation has been

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