COMPARISON OF SEDIMENTATION AND DISSOLVED AIR FLOTATION MODELING FOR CRYPTOSPORIDIUM REMOVAL

Moo-Young Han* and Won-Tae Kim
School of Civil, Urban and Geosystem Engineering, Seoul National University,
Seoul 151-742, Korea
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Abstract: Removal mechanisms for Cryptosporidium oocysts by sedimentation and dissolved air flotation (DAF) were investigated and compared using mathematical modeling. A set of trajectory analyses was performed for each process to estimate the collision efficiency of Cryptosporidium oocysts and other particles (i.e., floc particle or bubble). The sensitivity of a removal efficiency factor to major parameters of the treatment system was investigated for each process. Trajectory analysis modeling suggested that DAF is a better treatment option than sedimentation for the removal of Cryptosporidium. In sedimentation, floc size and floc zeta potential did not affect the collision efficiency.

In DAF, the collision efficiency factor greatly increased when the sign of the zeta potential of bubbles and Cryptosporidium oocysts was opposite. This theory could explain the current practice in DAF which emphasizes the importance of pretreatment. These theoretical predictions agreed well with experimental data obtained by others. An optimum bubble size for DAF was suggested. In addition, an improved DAF process using a positively charged bubble was proposed based on the theoretical analyses.

Key Words: collision efficiency, Cryptosporidium, oocysts, DAF, sedimentation, trajectory analysis, zeta potential

INTRODUCTION

There is growing concern over the risk to public health from waterborne pathogens such as Cryptosporidium. Although some of the treatment options such as sedimentation and DAF are used in water treatment plants, fundamental mechanisms of the processes are poorly understood. ¹)

The objective of this study was to investigate the heterogeneous collision mechanism between Cryptosporidium oocysts and other particles (i.e., floc particles in the sedimentation process and bubbles in the DAF process), as shown in Figure 1. Both cases are similar in mathematical formulation because the relative velocity of the other particle with respect to Cryptosporidium in a vertical direction is considered.

Sets of trajectory analyses were performed to calculate the collision efficiency factors of each process. The mathematical formulation used here for trajectory analysis takes into account both hydrodynamic and inter-particle forces. Collision efficiency factors between Cryptosporidium oocysts and particles were estimated as functions of the size and zeta potential of the colliding particles. The collision efficiencies of each process were then compared. Published experimental data were also used to check the model results.
TRAJECTORY ANALYSIS

The movement and collision of Cryptosporidium oocysts and other particles in a low Reynolds number, non-turbulent, flow regime can be illustrated by equations that include both hydrodynamics and inter-particle forces (i.e., van der Waals and electrostatic forces).

A detailed description of trajectory analysis is available elsewhere.\(^2,3\) Collision efficiency factors between Cryptosporidium oocysts and other particles (denoted as \(a_{ct}\) for oocyst-floc, and \(a_{cb}\) for oocyst-bubble) are defined by the equation shown in Figure 2.

The relative trajectory of a Cryptosporidium oocyst with respect to the other particle was calculated by integrating Equation (1).

\[
y' = \frac{dr}{d\theta} = s \cdot \frac{V_r}{V_o} = \frac{-\cos \theta L(s, \lambda) V_{42} - \frac{D_{42} G(s, \lambda) \nabla \Phi_{42}}{kT M(s, \lambda) \sin \theta V_{42}}}{s}
\]

where \(L, G\) and \(M\) are hydrodynamic functions that are determined from the center-to-center separation distance \(s\) and size ratio of Cryptosporidium oocyst to colliding particle \((\lambda)\), \(r\) and \(\Theta\) are the particle locations in polar coordinates, \(V\) is the particle velocity, \(D\) is the diffusion coefficient, \(k\) is the Boltzmann constant, \(T\) is the absolute temperature, and \(\Phi\) is a lumped inter-particle force parameter.

The interparticle force, as defined by DLVO theory, is a function of the size ratio of the two particles \((\lambda)\), the radius of the colliding particle \((A_p)\), the radius of the Cryptosporidium oocyst \((A_c)\), the center-to-center separation distance \((s)\), and the surface charges of colliding particles. Surface charge is related to the measurable zeta potential. Widely-used equations for van der Waals attraction and electric repulsion/attraction for two unequal particles were used. In calculating the attraction, a retarded attraction with a Hamaker constant \(A = 10kT\) was used.

A series of trajectory analyses, as defined above, were performed to investigate the effect of the size and zeta potential for each removal process. In the modeling, some parameter values appropriate to common conditions were, of necessity, adopted from values reported in the literature.

The size and density of a Cryptosporidium oocyst was taken as 5 \(\mu\)m and 1.07 g/cm\(^3\), respectively.\(^4\) The zeta potential of Cryptosporidium oocysts was taken as -25 mV, as reported by Karaman et al.\(^5\)

In the coagulation process, particles are removed either by adsorption and charge neutralization or by sweep coagulation. At low dosage, the zeta potential of Cryptosporidium oocysts may increase to zero or even become slightly positive by the mechanism of adsorption and charge neutralization.

However, at high dosage, hydroxide flocs are usually generated from aluminum or iron salt coagulants by the mechanism of sweep
coagulation. The size of the flocs varies from a few microns to hundreds of microns. Here, floc sizes of $2 \sim 100 \ \mu m$ were considered. Although the density of flocs decreases as the size increases, because of the water entrained within floc particles, their density was taken to be constant and set to $1.02 \ g/cm^3$. The zeta potential of hydroxide flocs is a function of pH of the solution and the solution composition. In this analysis, the zeta potential of alum floc particles was assumed to range between -30 and +10 mV.

The diameter of bubbles in DAF depends on the pressure and the design of the nozzle(s). However, the reported size range of air bubbles is between 20 and 100 $\mu m$. The zeta potential of bubbles has been measured by one of the authors. It is also pH dependent and varies between -10 and -25 mV. In this paper, the zeta potential of bubbles was taken to be -25 mV at pH 7. The density of bubbles was assumed to be 0.00117 g/cm$^3$.

Ionic strength of the solution affects the collision efficiency because of its effect on the thickness of the Debye-Hückel double layer. Here, the water was assumed to be fresh water, and ionic strength was set to 0.0001 M. The adopted conditions for the sensitivity analyses are summarized in Table 1.

## RESULTS

### Collision Efficiency of Cryptosporidium Oocysts and Floc ($\alpha_c$) in a Sedimentation Process

The predicted effects (by trajectory analysis modeling) of floc size on $\alpha_c$ are shown in Figure 4 for three values of floc zeta potential (-30 mV, 0 mV, +10 mV). The collision efficiency increased slightly for larger sized flocs, although the effect was minor. Collision efficiency is not sensitive to the zeta potential of floc.

The effect of floc zeta potential is shown in Figure 4 for the floc size of 100 $\mu m$. The collision efficiency factor was predicted to be very low regardless of the sign and magnitude of floc zeta potential.

It is expected from the theory that the removal of Cryptosporidium oocysts by differential sedimentation of floc is not very effective, regardless of the degree of pretreatment. Here, 'pretreatment' refers to changes in floc
when the oocyst charge was neutralized or became positive. This suggests that adequate coagulant pretreatment is very important to get a high efficiency.

The effect of bubble size on $\alpha_{cb}$ is shown in Figure 6 for three values of bubble zeta potential (-25 mV, 0 mV, +10 mV), although manipulation of the zeta potential of bubbles is seldom exploited in the normal DAF process. Collision efficiency was very low while the zeta potential of the bubble was negative, and there was no effect from varying bubble size. However, for zero or positive bubble zeta potentials there was a dramatic increase in collision efficiency, and modeling also predicted that there is an optimum size of bubble (2 $\mu$m) that produces the best collision efficiency with untreated *Cryptosporidium* oocysts. However, it is noted that this size is much smaller than that of bubbles normally used in DAF. Therefore, the practical recommendation based on theory is to use bubbles as small as practically possible to achieve a high removal of *Cryptosporidium* oocysts.

The effect of bubble zeta potential for a bubble diameter of 50 $\mu$m, which is in the size range of commonly produced bubbles, is as shown in Figure 7. While collision efficiency for non-negative zeta potentials increased by

**Collision Efficiency of *Cryptosporidium* Oocysts and Bubbles ($\alpha_{cb}$) in a DAF Process**

The effect of the zeta potential of *Cryptosporidium* oocysts on the collision efficiency is shown in Figure 5. Collision efficiency was very low for the negatively charged oocyst range, but abruptly increased by a factor of 10
and *Cryptosporidium* oocysts was the most important parameters for *Cryptosporidium* removal. The size of floc particles was found to be the next most important parameter. Adequate pretreatment is therefore essential to change the zeta potential of *Cryptosporidium* oocysts.

Plummer *et al.* performed batch experiments comparing the removal efficiencies for *Cryptosporidium* oocysts in the DAF and sedimentation processes.\(^8\) They found less than one log unit removal for sedimentation and more than two log units removal with DAF. DAF showed 10 times higher removal than sedimentation in the experimental condition.

Similar trends in removal efficiency were obtained from theory. The collision efficiency for sedimentation was predicted to be near 0.002, regardless of the size and zeta potential of flocs (Figures 3, 4). However, the predicted collision efficiency in DAF was predicted to be around 0.02 for a zero or positive zeta potential of *Cryptosporidium* oocysts (Figure 5). The theory therefore agreed well with the experimental results obtained by Plummer *et al.* (1995).\(^8\)

**CONCLUSIONS**

Collision efficiency factors for collision between *Cryptosporidium* oocysts and other particles in a non-turbulent regime were calculated from trajectory analysis for both sedimentation and DAF removal processes. The effects of particle size and zeta potential on collision efficiency were investigated.

Modeling suggested that the DAF process was capable of better efficiency than the sedimentation process, which agrees with experimental data obtained by others. The zeta potential of the bubble was predicted to be the most important parameter. However, in current DAF practice, the only controllable parameter is the size of bubble, not its potential.

The findings of these sensitivity analyses will help in the understanding and interpretation of the two main existing treatment op-

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**DISCUSSION**

From the theoretical modeling sensitivity analysis defined above, it was found that the zeta potential of both colliding floc particles
tions. They may also provide a useful guideline for developing a more efficient DAF method for removing Cryptosporidium through the control of bubble surface charge.

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