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Collision efficiency distribution of a bacterial suspension flowing through porous media and implications for field-scale transport

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ABSTRACT

The collision efficiency (α) distribution of a bacterial population was determined using multiple packed-bed columns of varying lengths and analyzing the bacteria clean-bed breakthrough concentrations using a distributed colloid filtration theory. This technique allows the α distribution to be determined independently from other effects that can cause non-exponential deposition, including detachment and blocking. It was found that multiple probability density functions (PDF's) could accurately replicate the experimental data. Regardless of which PDF was used, a distributed α resulted in significantly greater predicted field-scale transport than when using a single α. However, there were wide variations in the predicted field-scale transport between the different distributions, suggesting that lab-scale experiments may not be readily utilized to determine the specific PDF that best represents α at the field scale. Finally, blocking was observed in the column effluent curves, underscoring the fact that if non-clean-bed processes occur then an approach such as that utilized in the current study may be used to separate the non-clean-bed and clean-bed processes when determining the collision efficiency distribution.

1. Introduction and background

Bacterial transport through porous media is an important issue to environmental engineers and scientists for a variety of applications, including sand filtration for drinking water systems; movement of pathogenic organisms from on-site wastewater treatment systems to drinking water wells; and injection of bacteria into contaminated soils during bioaugmentation schemes. Bacterial transport has been studied at both the lab-scale and field-scale, and a common means to model this transport is through application of the colloid filtration theory (CFT) (Yao et al., 1971; Logan et al., 1995), which assumes a rate of removal of the form

$$\frac{dC}{dx} = -\lambda C, \tag{1}$$

where C is the colloid (bacteria) concentration and λ is the filter coefficient. The filter coefficient is dependent on the porous media, colloid and fluid properties, and the fluid flow conditions. It has been defined as (Yao et al., 1971; Logan et al., 1995)

$$\lambda = \frac{3}{2}\frac{(1-\theta)}{d_c}\alpha\eta_0, \tag{2}$$

where d_c is the diameter of the collectors (porous media grains), θ is the porosity, α is the collision efficiency, and η_0 is the single-collector contact efficiency. There are relationships available in the literature for calculating η_0, and a recently updated equation is provided by Tufenkji and Elimelech (2004a). The collision efficiency is typically the parameter determined through experimentation.

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Eq. (1) can be used as a loss term in the advection-dispersion equation to describe transport through porous media (Li and Johnson, 2005). Given a constant influx of colloids, the steady-state solution gives a commonly used form of the CFT:

$$\frac{C}{C_0} = \exp[-\lambda L], \tag{3}$$

where L is the travel distance through the packed bed, C is the colloid concentration exiting the packed bed, and C_0 is the initial colloid concentration entering the packed bed. It should be noted that direct application of the CFT assumes that the system is operating under "clean-bed" conditions. This assumption implies that the approaching colloids interact solely with the collector surface, resulting in exponential deposition within the column as a function of length as indicated by Eq. (3).

Researchers have found that non-exponential deposition often occurs during bacterial transport experiments. One process that may result in non-exponential behavior is cell detachment, and this can be accounted for in the advection-dispersion equation via a rate-limited detachment term (Li and Johnson, 2005). Another process that results in non-exponential behavior occurs when deposited bacteria "block" approaching bacteria from reaching the collector surface, and this is often modeled by adding a Langmuirian blocking term to the CFT filter coefficient (Rijnaarts et al., 1996; Brown and Jaffé, 2001a). It is important to note that clean-bed conditions exist when the bacterial front first passes through the packed bed, and this is termed the clean-bed breakthrough. Blocking and detachment may then occur after the clean-bed breakthrough as deposition results in adhered bacteria on the collectors.

It has also been found that non-exponential behavior occurs even when bacterial transport experiments were apparently operating under clean-bed conditions (Baygents et al., 1998; Simoni et al., 1998; Bolster et al., 2000; Tufenkji and Elimelech, 2004b; Tong et al., 2005). This discrepancy cannot be explained through variations in the porous media properties (Chen et al., 2001), and has lead many researchers to believe that α is not represented by a single value, but rather is a distributed parameter. Various distributions have been suggested for α, including the normal distribution (Tufenkji et al., 2003), bimodal distribution (Baygents et al., 1998; Simoni et al., 1998; Bolster et al., 2000), bimodal distribution composed of two normal distributions (Tufenkji and Elimelech, 2004b), lognormal distribution (Tufenkji et al., 2003; Tong et al., 2005) and Weibull distribution (Baygents et al., 1998). A power law formulation (e.g., a modified Beta distribution) has also been used (Redman et al., 2001; Tufenkji et al., 2003). The hypothesis that α is distributed is supported by studies that showed the electrostatic properties of bacterial cells to be distributed and this observed heterogeneity in cell surface charges has been correlated with variations in bacterial interactions with surfaces (Baygents et al., 1998; van der Mei and Busscher, 2001; Dong, 2002).

The potential for a distributed α is very important for studies investigating pathogen transport through the subsurface or through packed beds, such as sand filters, as any tail in the distribution towards small collision efficiencies (i.e., $\alpha \to 0$) has the potential to result in significant transport distances. As such, accurate determination of the collision efficiency distribution is required. Almost exclusively, studies investigating the collision efficiency distribution have focused on deposition patterns within packed beds. A key assumption for this technique is that the system is operating under clean-bed conditions, and any deviation from this assumption will result in errors when determining how α is distributed (Tufenkji et al., 2003). However, verification of this assumption is not always performed, partly due to the difficulty of verifying clean-bed conditions throughout the column.

Given the potential interferences of non-clean-bed processes and the number of different distributions suggested for describing α, the objectives of this study were to (a) develop a method for determining the collision efficiency distribution that is based solely on clean-bed processes; (b) explore the suitability of different collision efficiency distributions to replicate bacterial transport data; and (c) to explore the effects of extrapolating from lab-scale data to predicted field-scale transport. The approach employed focused on the clean-bed C/C_0 breakthrough values from a series of packed-bed columns that were operated under identical conditions, but with varying lengths. The distributed colloid filtration theory (described below) was used to fit a collision efficiency distribution to the clean-bed C/C_0 data, providing distribution parameters (e.g., mean and standard deviation for the Normal distribution) that best-fit the experimental data. Five different distributions were examined, including the bimodal, normal, lognormal, Weibull and Beta distributions. As described above, these distributions have been proposed by various researchers for representing the collision efficiency distribution, and one goal in this study was to determine if any one distribution fits the experimental data better than any of the others. These distributions were then used to provide predicted field-scale transport given the lab-scale data, highlighting the differences in transport characteristics obtained from the five different distributions.

2. Distributed colloid filtration theory model

The approach taken here is to isolate α by focusing on the clean-bed breakthrough concentration exiting a column containing a packed bed. Since α is defined by the initial clean-bed breakthrough concentration, this allows isolation of α from non-clean-bed processes such as blocking and detachment, negating the difficulties of separating these processes when looking at deposited colloids within the column. Assuming that α can be described by a distribution, the distributed colloid filtration theory can be written as

$$\frac{C}{C_0} = \int_0^1 P(\alpha)\, \exp[-\lambda(\alpha)L]\, d\alpha, \tag{4}$$

where $P(\alpha)$ is probability density function (PDF) of the distribution. For this study, the bimodal, normal, lognormal, Beta and Weibull distributions were considered. Additionally, uniform collision efficiency was used to determine if a single α can replicate the data from multiple column lengths. For these distribution models, the uniform collision efficiency can be considered a single-parameter PDF; the normal,