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A new method to evaluate polydisperse kaolinite clay particle removal in roughing filtration using colloid filtration theory

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ABSTRACT

Previous application of colloid filtration theory to roughing filtration has not considered a reliable method for determining a representative attachment factor for a polydisperse suspension (of constant particle density). Establishment of such a method would broaden the application of trajectory modelling in roughing filtration, and progress the development of a comprehensive database of attachment factors and surface charge potentials for various particle and fluid types. This study establishes a methodology for the application of colloid filtration theory to roughing filtration and incorporates recent advancements in theoretical single-collector efficiency.

A polydisperse kaolinite clay suspension was passed through a series of four gravel upflow roughing filters and removal efficiencies were calculated. Both the classical and Tufenkji and Elimelech's more recent correlation equations were used to calculate theoretical single-collector efficiencies and associated attachment factors for three different filter media sizes, flow rates, and suspended solids concentrations (0.137 ± 0.023). The use of Tufenkji and Elimelech's modified correlation equation resulted in reduced variability in the estimation of theoretical single-collector efficiencies.

1. Introduction

Roughing filters have often been employed as pre-filters to remove suspended solids and increase the operational life of slow sand filters (Collins et al., 1994; Wegelin, 1996; Ingallinella et al., 1998). Wegelin (1996) reports that roughing filter removal efficiencies with respect to turbidity are generally high (0.85–0.90) for high turbidity (150–500 nephelometric turbidity units, NTU) but decrease (0.80–0.85) during periods of moderate turbidity (30–50 NTU).

Previous studies have demonstrated the predominance of physico-chemical processes for particle removal in filters (Yao et al., 1971; Wegelin, 1996; Tufenkji and Elimelech, 2004). In the assessment of these processes for roughing filter applications, where the particles to be removed are orders of magnitude smaller than the filter media, the particle removal efficiency is dominated by the successful transport and attachment of a particle to the media (or collector) surface. This is described by the trajectory approach to modelling deep-bed filters and is evaluated using colloid filtration theory (CFT) (Yao et al., 1971).

The development and subsequent evaluation of particle removal efficiency using CFT has been performed by passing monodisperse suspensions of microspheres through packed columns and varying parameters such as ionic strength, ion valence, particle size, media size and hydraulic loading rates

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(Elimelech and O'Melia, 1990; Elimelech, 1991, 1994; Liu et al., 1995; Li et al., 2005). These investigations have progressed the theory, but the evaluation of polydisperse suspensions, as found in many real applications, using nonspherical particles such as kaolin, has to date not been investigated with the more recent derivations of the CFT theory (Tufenkji and Elimelech, 2004).

In the trajectory model approach, the three dominant processes governing transport of particles to a collector are diffusion, interception, and sedimentation. Diffusion represents the dominant process for small particles (<1 μm), whereas interception and sedimentation dominate for larger particles. The diffusion process, η_D, is as described by Yao et al. (1971):

$$\eta_D = 0.9\left(\frac{kT}{\mu d_p d_c v}\right)^{2/3}, \tag{1}$$

where k is the Boltzmann constant, T the absolute temperature, μ the fluid dynamic viscosity, d_p the average particle diameter, d_c the average collector diameter, and v the fluid approach velocity.

Interception is defined as occurring when a particle following a fluid streamline comes in contact with a collector. Particle removal by interception, η_I, is as described by Yao et al. (1971):

$$\eta_I = \frac{3}{2}\left(\frac{d_p}{d_c}\right)^2. \tag{2}$$

Sedimentation, η_G, occurs when a particle is transported out of its fluid streamline to a collector surface due to gravitational settling and is described by Yao et al. (1971) as the ratio of settling velocity (as determined by Stokes' Law) to the hydraulic loading rate:

$$\eta_G = \frac{(\rho_p - \rho_f) g d_p^2}{18\mu v}, \tag{3}$$

where ρ_p is the particle density, ρ_f the fluid density, and g the gravitational constant. The sum of these three processes (Eqs. (1)–(3)) serve as the basis for the theoretical single-collector efficiency (SCE or η_{total}), which is the ratio of the rate at which particles strike a collector surface to the rate at which particles flow towards that collector:

$$\eta_{total} = 0.9\left(\frac{kT}{\mu d_p d_c v}\right)^{2/3} + \frac{3}{2}\left(\frac{d_p}{d_c}\right)^2 + \frac{(\rho_p - \rho_f) g d_p^2}{18\mu v}. \tag{4}$$

Eq. (4) was most recently refined by Tufenkji and Elimelech (2004) to consider close range forces, including hydrodynamic interactions and universal van der Waals attractive forces. The refined SCE correlation equation is defined by Tufenkji and Elimelech (2004) as

$$\eta_{total} = \eta_D + \eta_I + \eta_G = 2.4 A_s^{1/3} N_R^{-0.081} N_{Pe}^{-0.715} N_{vdW}^{-0.052} + 0.55 A_s N_R^{1.675} N_A^{0.125} + 0.22 N_R^{-0.24} N_G^{1.11} N_{vdW}^{-0.053}, \tag{5}$$

where A_s is the porosity-dependent parameter of Happel's model; $A_s = 2(1-\gamma^5)/(2-3\gamma+3\gamma^5-2\gamma^6)$ and $\gamma = (1-\varepsilon)^{1/3}$, where ε is the porosity of the media. Happel's model is a commonly used approximation for the flow field around spherical collector (Tien, 1989). $N_R = d_p/d_c$ (aspect ratio), $N_{Pe} = vd_c/(kT/3\pi d_p \mu)$ (Peclet number characterising the ratio of convective to diffusive transport (later described by Stokes–Einstein equation)), $N_{vdW} = A/kT$ (van der Waals number characterising the ratio of van der Waals interaction energy to the particle's thermal energy; A is the Hamaker constant of the interacting media (i.e. 1.6×10^{-21} for quartz (Ackler et al., 1996)), $N_A = A/12\pi\mu(d_p/2)^2 v$ (attraction number; combined influence of van der Waals attraction forces and fluid velocity on particle deposition by interception), and $N_G = (\rho_p - \rho_f) g d_p^2/18\mu v$ (gravity number; ratio of Stokes particle settling velocity to approach velocity of fluid).

Fig. 1 illustrates that the incorporation of hydrodynamic and van der Waals attractive forces affects the calculation of the SCE for representative particles. For particles >1 μm, a slightly smaller theoretical SCE value is calculated using Eq. (5) compared with Eq. (4). These differences decrease for large particle sizes (>10 μm). Physico–chemical conditions are often unfavourable to particle-collector attraction and the actual single-collector efficiency, η, will be less than the theoretical value, η_0:

$$\eta = \alpha \eta_0, \tag{6}$$

where α is the attachment factor, an empirical collision efficiency factor. When $\alpha = 1$, the solution is completely

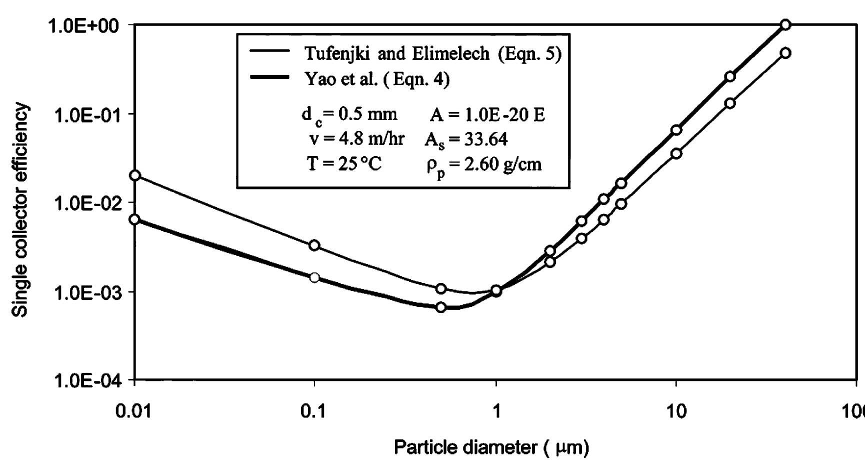

Fig. 1 – Comparison of the theoretical single-collector efficiency (η) using equations developed by Yao et al. (1971) and Tufenkji and Elimelech (2004) for representative inorganic particles.