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Influence of particle concentration on initial collection efficiency and surface coverage in porous media filtration

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Abstract−Four sizes (0.095, 0.53, 1.0 and 2.01 μm) of polystyrene latex particles were used to prepare monodispersed suspensions at three different ionic strengths (10^{-3}, $10^{-2.5}$ and 10^{-2} M KCl). Filtration experiments were conducted using those suspensions in a filter column with glass beads as porous medium. The filter bed depth and the filtration velocity were kept at 5 cm and 1 m/h, respectively. When suspensions with equal mass concentrations (0.2 mg/L) or equal surface area concentrations (0.12 cm^2/mL) were filtered through the system, the largest particles exhibited higher initial single collector efficiency, η. The difference between the η of largest particles and the smaller particles was prominent for suspensions with equal surface area concentrations at higher ionic strengths. The collision efficiency, α of those particles exhibits higher values at higher ionic strengths. Both at equal mass concentration and equal surface area concentration, α is only slightly dependent on particle sizes when compared to its dependence on ionic strength. Further, it was found that the specific surface coverage was similar for 0.095 μm, 0.53 μm and 1.0 μm particles during the transient stage of filtration at any ionic strength when the surface area concentrations of those suspension were equal.

Key words: Collision Efficiency, Initial Single Collector Efficiency, Ionic Strength, Latex Particles, Porous Media Filtration, Specific Surface Coverage

INTRODUCTION

The importance of porous media filtration is obviously significant in water and wastewater treatment. Porous media filtration has been used as the final clarifying step in water treatment for over a century and it is becoming increasingly important in the tertiary treatment step of wastewater treatment to produce effluent of superior quality for the purpose of reuse. Basically, porous media filtration plays the main role in removing particles of various natures and sizes, which are present in water and wastewater. These particles range from 0.1 μm to 100 μm in size, including microorganisms such as bacteria, protozoa (cryptosporidium, giardia) etc. [Jegatheesan, 1999]. It is popular in water and wastewater treatment due to its reliable and steady production of high quality water at a reasonably low cost. The porous media filter is usually placed after sedimentation units to remove suspended particles that escape without settling in the sedimentation units in water or wastewater treatment plants [Jegatheesan et al., 2005].

The removal of particles in a porous media filter requires two major successive steps: the transportation of particles to the filter grains or the previously deposited solids and the attachment of the particles to the surface of filter grains after contacts occur. The particles are transported to the filter grain by various transport mechanisms such as diffusion, sedimentation, interception, inertia and hydrodynamic effect [Chang, 1989; So et al., 2004]. When the particles are being transported to the filter grain, forces acting between the particles and filter grain dictate the effective removal of the particles. These forces can be either attractive or repulsive and they start to act when the separation distance between particles and filter grain becomes on the order of nanometers (nm). These forces are only dominant at a very short range but are important in explaining the particle removal from a flowing suspension. These forces can be mainly divided to four types: van der Waal's force (F_V), electric double-layer force (F_e), Born force (F_B) and hydration force (F_h) [Raveendran, 1993]. The total adhesive force is the algebraic sum of the four forces mentioned above. The chemistry of the porous media system is determined to be of great importance in affecting these forces, which eventually affects the removal performance of the filter.

Generally, the factors affecting the performance of a porous media filter are the ionic strength and pH of suspension, particles size, and their size distribution in the suspension, presence of organic substances in a suspension, filter depth, duration of filtration, shape and density of filter grains, filtration velocity, viscosity of the suspension, surface characteristic of particles, filter grains and the coagulants used etc. [Jegatheesan, 1999; Chang, 1989; Jegatheesan and Vigneswaran, 1997; Choi et al., 2005]. In addition, particle removal efficiency also depends on the particles concentration in suspension, which can be measured in terms of mass (mg/L), number (no. of particles #/mL) and surface area (cm^2/mL).

1. Particle Concentration in Suspension

Influent particle concentration is a factor that influences the overall performance of a porous media filter besides the physical and chemical characteristics of particles and filter media. Particle concentration can be measured in terms of mass (mg/L), number (No. of particles #/mL) and surface area (cm^2/mL). There are filtration models available in the literature, which include a concentration term either implicitly or explicitly. However, it is still elusive whether the concentration should be expressed in terms of number, mass or sur-

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face area [Jegatheesan and Vigneswaran, 1997]. In this study, careful porous media filtration experiments were conducted to understand the effect of concentration of different sizes of particles (0.095 to 2.01 μm) at several ionic strengths (10^{-3}, $10^{-2.5}$ and 10^{-2} M KCl) on the initial collection efficiency of a porous medium. The relative importance of concentration expressed in terms of mass and surface area of particles was investigated as well.

2. Mathematical Formulations for Filter Efficiency

Many researchers [O'Melia and Stumm, 1967; O'Melia et al., 1978; Ives, 1970; Tien, 1989; Elimelech, 1989; Hahm et al., 2003] have discussed the factors responsible for removal of suspended solids within the filter. Their researches could be broadly classified into two major groups, macroscopic and microscopic approaches. The macroscopic approach deals with the cumulative collection of deposits, while the microscopic approach considers the individual particle size and the number of particles. In the macroscopic approach, the physical and chemical characteristics of a suspension and the flow field of a granular bed are not explicitly accounted for. The effects of such parameters as particle size, particle type and solution chemistry are implicitly included in the value of filter coefficient, λ. The value of λ is determined from results which cannot usually be applied to other filtration systems. The microscopic approach is developed in order to describe the effects of suspension characteristics on filtration behaviour in a fundamental and predictable manner. Here, the filter bed is modeled as an assemblage of single or unit collectors. In this approach, a number of porous media models have been proposed to study the various physical or chemical phenomena.

3. Initial Single-Collector Removal Efficiency, η

The performance of a filter is expressed in terms of single-collector removal efficiency (η) which is as follows [Yao et al., 1971]:

$$\eta=\frac{\text{Quantity of particles in contact with the collector in a unit}}{(\pi a_c^2)UN_o} \tag{1}$$

Where a_c is the radius of the collector (filter grain), U is the filtration velocity and N_o is the particle number concentration. A single filter grain is termed as a collector. If the value of the single-collector removal efficiency is known, the efficiency of the entire bed depth can be calculated by the following equation:

$$[C/C_o)]=\exp[(-3/2)\times(1-f_o)\times\alpha\eta_o\times L/a_c] \tag{2}$$

where C and C_o is the effluent and influent concentration respectively, η_o is the single-collector contact efficiency, and α is the collision efficiency which is defined as the ratio between the number of contacts which succeeded in producing adhesion and the number of collisions which occur between suspended particles and the filter grain. Ideally, α is equal to unity in a completely destabilized system [Elimelech, 1989, 1992; Tufenkji and Elimlech, 2004].

Under the conditions of most aquatic systems, the actual single-collector removal efficiency (η) is lower than the single-collector contact efficiency (η_o) due to repulsive colloidal interactions between particles and collectors. The actual single-collector removal efficiency (η) is often expressed as a product of collision efficiency (α) and the single-collector contact efficiency (η_o) as:

$$\eta=\alpha\eta_o \tag{3}$$

Since the current theories are inadequate to predict the collision efficiency (α), it is often common to use column experiments to determine the collision efficiency for a given physicochemical conditions (i.e., suspended particles, porous medium and solution chemistry). By Eq. (2), single-collector removal efficiency (η) is obtained from experiment data and this value together with the single-collector contact efficiency (η_o) predicted by theoretical equations can be used to compute collision efficiency (α) with the use of Eq. (3).

4. Initial Single-Collector Contact Efficiency (η_o)

During the past two decades, many mathematical models have been put forward to predict single-collector contact efficiency (η_o). Some of the mathematical models used to calculate the single-collector contact efficiency are given in Table 1. For example, the models presented by Yao et al. [1991] and others take into consideration the diffusion, sedimentation and interception aspects of transport of particles, but they do not account for hydrodynamic drag and London-van der Waals forces. The model developed by Rajagopalan and Tien (RT) [Rajagopalan and Tien, 1976] includes these phenomena and is more comprehensive in predicting the contact efficiency (η_o) of a single-collector. However, the RT equation has several limitations that render the equation inaccurate for prediction of filtration efficiency for most conditions of practical relevance. The major shortcoming of the RT equation is the omission of the influences of hydrodynamic and van der Waals interactions on the deposition of particles that are dominated by Brownian diffusion.

A more accurate and complete expression for predicting the single-collector contact efficiency (η_o) was presented by Tufenkji and Elimelech [2004]. The dimensionless parameters governing the trans-

Table 1. Mathematical models used to calculate contact efficiency of collector (1)

Model used	Contact efficiency, η_o	
Stokes	Levich [1962]:	$\eta_D=0.9\ N_{Pe}^{-2/3}$
	Yao et al. [1971]:	$\eta_I=1.5\ N_R^2$
		$\eta_G=N_G$
		$\eta_o=\eta_1+\eta_G+\eta_D$
Happel	Happel [1958]:	$\eta_I=1.5\ A_S\ N_R^2$
	Cookson [1970]:	$\eta_D=0.9\ A_S^{1/2}\ N_{Pe}^{-2/3}$
	Rajagopalan and Tien [1976]:	$\eta_o=4\ A_s^{1/3}\ N_{Pe}^{-2/3}+(1-f_o)^{2/3}\ A_s\ N_{Lo}^{1/8}\ N_R^{15/8}+3.375\times10^{-3}\ (1-f_o)^{2/3}\ A_S\ N_G^{1.2}\ N_R^{-0.4}$
	Tobiason [1988]:	$\eta_o=4\ A_S^{1/3}\ N_{Pe}^{-2/3}+A_S\ N_{Lo}^{1/8}\ N_R^{15/8}+3.38\times10^{-3}\ A_S\ N_G^{1.2}\ N_R^{-0.4}$
Kuwabara	Lee and Gieskie [1979]:	$\eta_D=3.54\ [f_o/K_w]^{1/3}\ N_{Pe}^{-2/3}$
		$\eta_I=1.5\ [f_o/K_w]\ N_R^2/[N_R+1]^2$

port mechanisms such as Brownian diffusion, interception and gravitational sedimentation were regressed against the theoretical single collector efficiency derived from the convective-diffusion equation. This new correlation of single-collector contact efficiency can be given by Tufenkji and Elimelech [2004]:

$$\eta_o=2.4\,A_S^{1/3}\,N_R^{-0.081}N_{Pe}^{-0.715}N_{vdW}^{0.052}+0.55\,A_S\,N_R^{1.675}\,N_A^{0.125} + 0.22\,N_R^{-0.24}\,N_G^{1.11}\,N_{vdW}^{0.053} \tag{4}$$

where the parameters and definitions are given in the nomenclature.

5. Collision Efficiency (α)

According to theoretical prediction, particle size has a marked effect on the collision efficiencies in the region of unfavorable deposition [Elimelech, 1989]. It predicts that at given chemical conditions, the collision efficiencies decrease as the particle size of the suspension increases. A common feature in colloid deposition studies is the large discrepancy between observations and theory. The lack of dependence of experimental collision efficiencies on particle size has led to a formulation of an empirical relationship between collision efficiencies assuming that the particle size has no effect on the actual collision efficiency [Elimelech, 1989]. Hence, the collision efficiency has the following general dependence:

$$\alpha=g\,(\Theta,\,\kappa,\,H),\ \text{where}\ \Theta=\varepsilon_o\varepsilon_r\Psi_1\Psi_2 \tag{5}$$

The dimensional analysis yields the following linearized form:

$$\log\alpha=\log B+n\log(\kappa H/\Theta) \tag{6}$$

where B and n are constants to be determined from experimental values of ($\kappa H/\Theta$) and α.

Tien and Bai [1996] developed a correlation for the initial collision efficiency under unfavorable surface interactions. A correlation between α and the four dimensionless parameters identified from the partial regression analysis was established as:

$$\alpha=10^{-2.9949}\,(N_{LO})^{0.8495}\,(N_{E1})^{-0.2676}\,(N_{E2})^{3.8328}\,(N_{DL})^{1.6776} \tag{7}$$

where N_{LO} is the London number ($=4H/(9\pi\mu d_p^2U)$), N_{E1} is the first electrokinetic parameter ($=\varepsilon_o\varepsilon(\xi_p^2+\xi_g^2)/(3\pi\mu Ud_p)$), N_{E2} is the second electrokinetic parameter ($=2\xi_p\xi_g/(\xi_p^2+\xi_g^2)$) and N_{DL} is the double layer force parameter ($=\kappa d_p$). The subscripts p and g denote particles and collectors, respectively. The definitions of parameters that appear in the above expressions are given in the nomenclature. Generally Tien and Bai's [1996] correlation equation shows better agreement between predicted and the corresponding experimental α values if compared to Elimelech's equation. However, they are still considered not adequate to predict a for various physicochemical conditions and systems.

5. Specific Surface Coverage

Particle deposition in a porous media filter can be described by the changing rate at which the filter grain surfaces are covered by deposited particles. Therefore, the specific surface coverage (θ) in a time interval (Δt) is defined as the ratio between the surface area of filter grains that is covered by deposited particles in a unit bed volume in Δt and the total surface area of filter grains in a unit bed volume. The specific surface coverage from t=0 to t=t can be calculated by using the following expression [Johnson and Elimelech, 1995; Jegatheesan and Vigneswaran, 2000]:

$$\{(\pi a_p^2)UN_oa_c/[3L(1-f_o)]\}\int_0^t(1-N/N_o)dt \tag{8}$$

In deriving this expression, monolayer coverage of particles onto filter grains is assumed [Jegatheesan and Vigneswaran, 1997]. By considering specific surface coverage, one can determine and investigate the performance of a porous media filter by considering how much surface area of filter grains is covered by particles after a period of time. The effect of concentration of particles expressed in terms of mass and surface area on porous media filtration can well be noticed and discussed by considering specific surface coverage. The expression of specific surface coverage gives a clear indication of the accumulation of particles, which are captured and entrained on the surface of filter grains over a period of time.

EXPERIMENTAL SET-UP

1. Experimental Porous Media Filter System

A filter column made of acrylic plastic was designed and used in conducting the various experiments in this study. The length of the acrylic filter column was 25 cm and the column had an inner diameter of 7.5 cm. A constant head tank was connected to the filter column to supply suspension at constant head. The inlet and outlet ports of the filter column were connected to manometer tubes to assist in monitoring the head loss development. The outlet of the filter column was connected to a flow-adjusting valve to constantly monitor and regulate the flow. It was then connected to the sample collection system. All the tubes connecting the filter column to constant head tank, manometer tubes and sample collection system were made of plastic (polyvinyl chloride).

2. Materials

2-1. Suspended Particles

Polystyrene latex particles of various submicron and above micron sizes were used as suspended particles in the suspension. These polystyrene latex particles of known sizes were commercially purchased from Proscitech Co., Australia and they were manufactured by Spherotech Inc., USA. The properties of polystyrene latex particles used in this study are given in Table 2.

2-2. Filter Grains (Collectors)

Spherical glass beads of 0.1 mm diameter were used as filter grains (collectors) in all the filtration experiments. The density of glass beads used was 2,830 kg/m^3. They were commercially purchased from Daintree Scientific Co., Australia. Chemicals: Potassium chloride (KCl), which is a 1 : 1 electrolyte, was used to control and alter the ionic strength of the suspension. Before a suspension of latex particles was prepared, a known quantity of KCl was added to the water to control or modify the ionic strength of suspension to the desired value. It was also used to prepare tracer solution when tracer experiments were conducted. Sodium hydroxide (NaOH) and nitric acid (HNO_3) were used intensively during the cleaning of the glass

Table 2. Properties of polystyrene latex particles used in current study

Particles diameter (nominal)	0.1 μm, 0.5 μm, 1.0 μm, 2.0 μm
Particles diameter (actual)	0.095 μm, 0.53 μm, 1.0 μm, 2.01 μm
Density	1,050 kg/m^3
Refractive index	1.59
Shape	Uniform microsphere
Porosity	Non-porous

beads. They were used to prepare their own solution of desired concentration in order to clean the glass beads before the first use and after every run of experiments.

3. Methods

3-1. Glass Beads Cleaning

Before the use of the glass beads as collectors in the filtration experiments, they were cleaned thoroughly to remove any dirt or unwanted particles attached to them during the manufacturing phase. In addition, they were also cleaned after each filter run to remove the suspended particles entrained on them. The method adopted by Tobiason [1987] was used to clean the glass beads in this study. Preparation of Polystyrene Latex Particles Suspension: Known amount of potassium chloride (KCl) was maintained or added to the water to obtain a solution of desired ionic strength. pH meter (*model: Aqua - pH (TPS)*) and conductivity meter (*model: WP81 pH - conductivity - salinity (TPS)*) were used to measure and monitor the pH and ionic strength of the solution, respectively. Latex particles were diluted into this solution to the required concentration. The suspension was then used for filtration experiment within an hour of preparation. In all the suspensions prepared, no aggregation of particles was observed.

3-2. Filter Column Packing

The filter column had to be packed with glass beads to a specific bed depth of 5 cm. Before the actual packing of glass beads, the required amount of glass beads needed to fill a bed depth of 5 cm was calculated. This amount was determined in terms of weight, and this weight of glass beads was constantly used to pack the column in all the experiments that followed. Generally, the porosity of the filter bed varied from 0.32 to 0.34, which was considered a small variation. The porosity value measured in each experiment was incorporated in the computations. pH Stabilization: Before the experiments commenced, the packed filter column was allowed to filter clear solution with similar chemistry. A passage of clear solution through the filter column for a period of time was required to bring the effluent pH closer to the influent pH. An increase of pH was predicted when the solution passed through the glass beads due to the uptake of H^+ from the solution by the glass beads and the release of Na^+.

Generally, the pH of the effluent was stabilized after a passage of clear solution for half an hour before the commencement of each experiment. The actual filtration experiments were conducted only after the stabilization of pH.

4. Experiments

4-1. Tracer Experiments

Tracer experiments were conducted prior to the filtration experiments to characterize the flow pattern through the packed bed. The time corresponding to the initial removal of particles of the clean bed was determined by tracer experiment. After the column was packed with glass beads and filtration conducted with clear water to stabilize the pH of the effluent, tracer solution was passed through the filter column at required flow rate. A solu- tion of 10^{-2} M KCl was used as a tracer in these experiments. The concentration of the tracer in the influent and the effluent was then determined by measuring the conductivity (conductivity meter model: WP81 TPS). The influent conductivity value was measured initially and the effluent conductivity values were taken at every 5 minutes time interval from the commencement of a tracer experiment. The time at which the ratio of effluent conductivity (T_r) and influent conductivity (T_o) becomes 0.99 (T_r/T_o=0.99) was used to compute the initial collection efficiency of the filter in the subsequent filtration experiments.

4-2. Filtration Experiments

Before the filtration experiments commenced, the column was packed with glass beads and clear solution with same ionic strength was filtered to stabilize the pH of the effluent. After the pH was stabilized, pre-prepared latex suspension (influent) with known concentration was fed continuously from the constant head tank to the filter column. The effluent was then sampled at every 10 minute time interval and the concentration of each sample was measured. In addition, the head loss development was monitored prior to every sampling and the pH value of effluent was measured once an hour. Since the experiments were carried out with monodispersed suspensions, the turbidity measurements of influent and effluent were directly proportional to the concentration of particles. Therefore, a highly accurate turbidity meter (*model: HACH 2100P Turbidimeter*) was used to measure the turbidity of the influent and the effluent samples.

RESULTS AND DISCUSSION

1. Filtration Experiments

Polystyrene latex particles with diameters of 0.095 μm, 0.53 μm, 1.0 μm and 2.01 μm were used to prepare monodispersed suspensions at known concentration, while glass beads of 0.1 mm diameter were used as filter grains. The experiments were conducted on the laboratory scale filter column described in the previous section. All the experiments were conducted under constant bed depth (5 cm) and constant head velocity (1 m/h). In order to understand the relative importance of influent concentration expressed in terms of mass, number or surface area of particles, 21 experiments on porous media filtration were conducted with the above-mentioned latex particles. Latex particle suspensions were prepared at three different ionic strengths (10^{-3}, $10^{-2.5}$ and 10^{-2} M KCl). Influent concentration of the suspensions was kept at 0.2 mg/L for each particle to conduct experiments under equal mass concentration (12 experiments). Suspensions with influent concentrations of 1.1, 2.1 and 4.2 mg/L were prepared for 0.53, 1.0 and 2.01 μm latex particles, respectively, at the above-mentioned ionic strengths to conduct experiments with equal surface area concentrations (9 experiments). From Table 3, it can be seen that monodispersed suspensions having concentrations of 0.2 mg/L of 0.095 μm particles, 1.1 mg/L of 0.53 μm particles, 2.1 mg/L of 1.0 μm particles and 4.2 mg/L of 2.01

Table 3. Relationship between surface area concentrations with the influent mass concentration of particles

Influent mass conc. C_o (mg/L)	Particle size/Influent surface area conc., A_o (cm^2/mL)			
	0.095 μm	0.53 μm	1.0 μm	2.01 μm
0.2	**0.120300**	**0.021563**	**0.011428**	**0.005685**
1.1	0.661654	**0.118598**	0.062857	0.031272
2.1	1.263157	0.226415	**0.120000**	0.059701
4.2	2.526315	0.452830	0.240000	**0.119402**

(7 experiments/ionic strength×3 ionic strengths=21 experiments)

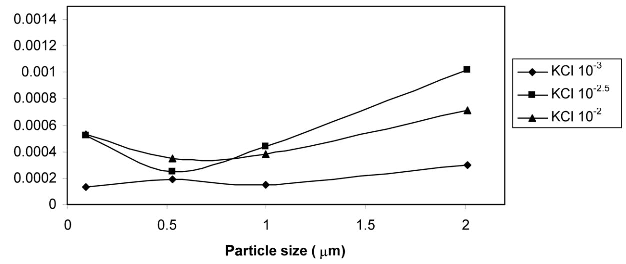


Fig. 1. Initial single-collector removal efficiencies (η) at equal mass concentration of particles (Equal mass concentration - 0.2 mg/L).

μm particles will have a surface area concentration of 0.12 cm^2/mL.

2. Effect of Influent Concentration on Initial Efficiency

The initial single-collector removal efficiency, η, corresponding to the particle sizes of 0.095, 0.53, 1.0 and 2.01 μm are presented in Fig. 1. Variations of η with respect to the change of influent mass concentration of a given size of particles are noticeable especially when the ionic strength of the suspension is high. It can be observed that η decreases with an increase in the influent concentration of smaller particles (0.53 μm and 1.0 μm). This is not the case for larger particles (2.01 μm) where η increases with an increase in influent concentration. These phenomena could obviously be observed at high ionic strengths ($10^{-2.5}$ M KCl and 10^{-2} M KCl). It can be concluded that diffusion, which is dominant in the transport of Brownian particles to the filter grains, is larger at low particle concentrations. On the other hand, the sedimentation, which is dominant in the transport of above micron particles to the filter grains, is larger at high particle concentrations. Further, h values are higher at high ionic strengths (10^{-2} M KCl and $10^{-2.5}$ M KCl).

3. Effect of Equal Mass and Equal Surface Area Concentration of Particles on η

The η obtained experimentally for experiments conducted for different sizes of particles at constant mass concentration of 0.2 mg/L and constant surface area concentration of 0.12 cm^2/mL are presented in Figs. 1 and 2, respectively. It can be observed that for both constant mass and constant surface area concentrations, the largest particles (2.01 μm) exhibit highest initial single-collector removal efficiency compared to smaller particles (0.095 μm, 0.53 μm and 1.0 μm) at all ionic strengths of the suspension. This can obviously be noticed at high ionic strength ($10^{-2.5}$ M KCl and 10^{-2} M KCl) where there are significantly large differences between the η of 2.01 μm particles and the η of smaller particles (0.095 μm, 0.53 μm and 1.0 μm). At equal surface area concentration of different particles, the difference between the η of 2.01 μm particles and the η of smaller particles is larger compared to the differences at equal mass concentration. This larger difference could be noticed at 10^{-2} M KCl and 10^{-3} M KCl ionic strength.

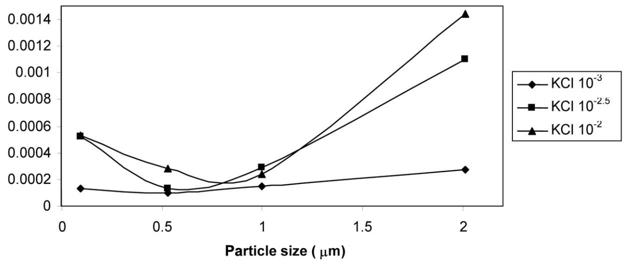


Fig. 2. Initial single-collector removal efficiencies (η) at equal surface area concentration of particles (Equal surface area concentration - 0.12 cm^2/mL).

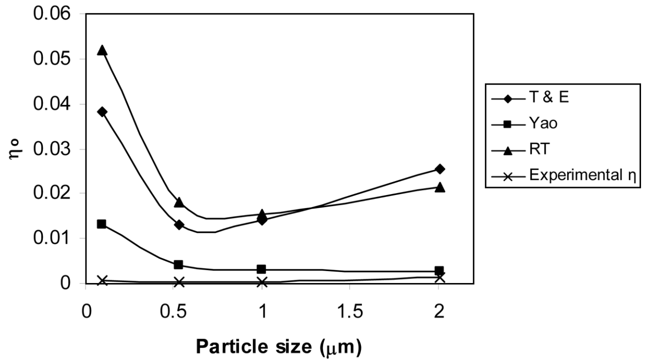


Fig. 3. Comparison of experimental single-collector removal efficiencies (η) and theoretical initial single-collector contact efficiencies (η_o) (d_c=0.1 mm, U=1 m/h, f_o=0.32 and T=25 °C) (T & E - Tufenkji & Elimelech, RT - Rajagopalan & Tien).

4. Comparison of Experimental η and Theoretical Computation of η_o

In Fig. 3, theoretical values of initial single-collector contact efficiency (η_o) calculated by using Tufenkji & Elimelech (T & E), Yao, Rajagopalan & Tien (RT) equations and experimental η are plotted against the particle sizes. It can be observed from Fig. 3 that the initial η_o of a given size of particles predicted by more recent correlations (Tufenkji & Elimelech and Rajagopalan & Tien) are closer to each other, while the initial η_o of that given size of particles predicted by Yao's equation is much less than those values. The minimum η_o among the 4 particles occurs at 0.53 μm and 1.0 μm. This minimum can also be observed in experimental η. Hence the experimental results complied with theoretical results where minimum η exists for particles of 0.53 μm and 1.0 μm.

The theoretical predictions seem to underestimate the initial η_o of 2.01 μm particles. Experimentally, initial η of 2.01 μm particles was determined to be the highest among the 4 particles. However, this is not the case for the theoretical prediction where the smallest particles (0.095 μm) seem to give the highest initial η_o among the 4 particles. The theoretical values of η_o are significantly higher than the values of experimental η due to the low collision efficiencies, α of filtration under unfavorable conditions where particles did not produce sufficient attachment although the rate of contact with the filter grains was high ($\eta=\alpha\eta_o$). The theoretical prediction of η_o does not account for the chemical condition of the filtration system. Accurate prediction can only be achieved when a favorable condition is considered (α=1).

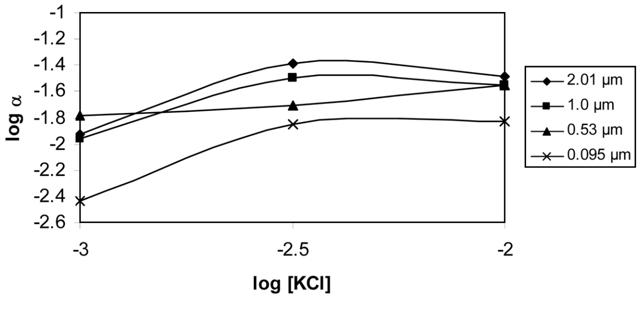
5. Collision Efficiency (α)

Due to the inadequacy in predicting η, initial collision efficiency (α) was calculated by using the experimental initial single-collector removal efficiency (η) and the calculated initial single-collector contact efficiency (η_o) estimated by the Tufenkji & Elimelech equation. Fig. 4 presents the initial collision efficiencies (α) computed for each physicochemical condition of filtration. From Fig. 4, one can utilize the values of α and the estimation of η_o by T&E equation to predict the actual initial single-collector removal efficiencies (η) for the experiments conducted under reasonable physicochemical similarity to the experiments carried out in this study. Overall, the α exhibits higher values at higher ionic strengths. At either equal mass concentration or equal surface area concentration, α is only slightly dependent on particle sizes when compared to its dependence on ionic strength.

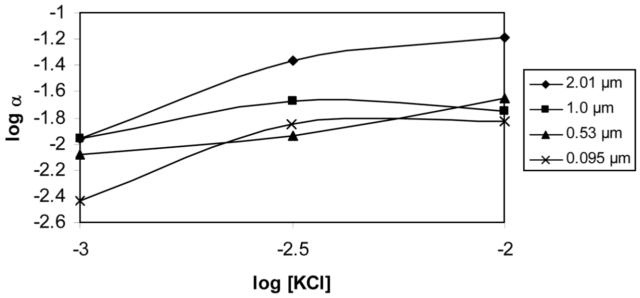
6. Transient Stage Efficiency

6-1. Effect of Equal Mass and Equal Surface Area Concentration on Transient Stage Efficiency

Figs. 5, 6 and 7 show the comparisons of particle removal effi-

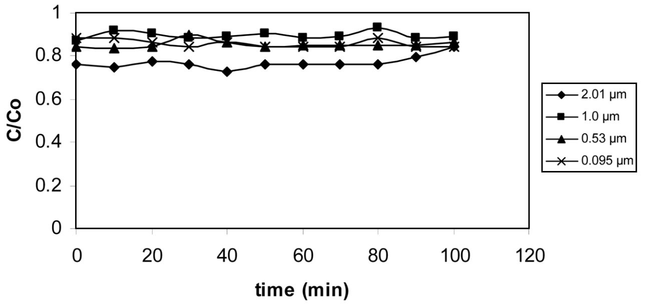


(a) Equal Mass

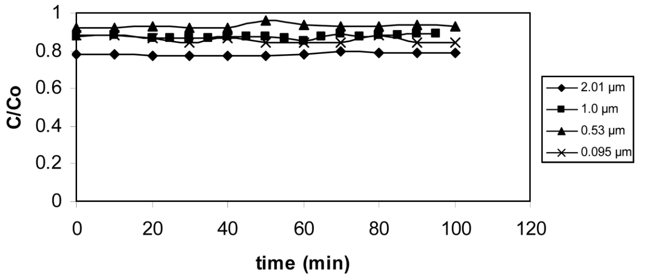


(b) Equal Surface Area

Fig. 4. Initial collision efficiencies (α) at different ionic strength for different particles (Equal mass concentration - 0.2 mg/L; Equal surface area concentration - 0.12 cm^2/mL).

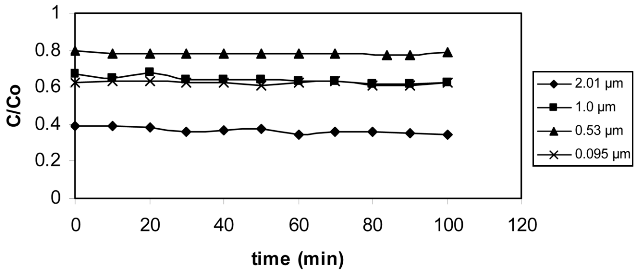


(a) Equal Mass

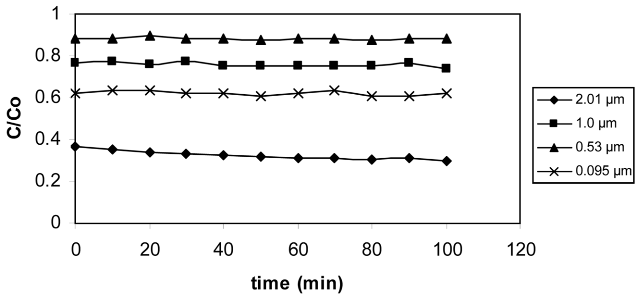


(b) Equal Surface Area

Fig. 5. Particle removal efficiencies at equal mass and equal surface area concentration under 10^{-3} M KCl (Equal mass - 0.2 mg/L, Equal surface area - 0.12 cm^2/mL).

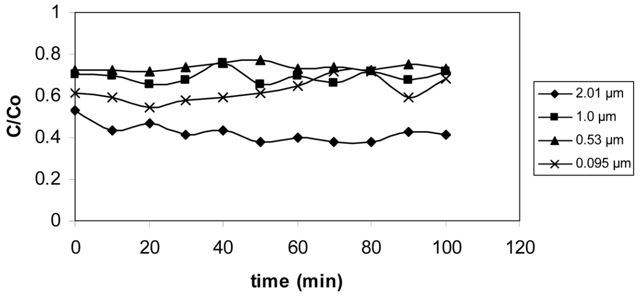


(a) Equal Mass

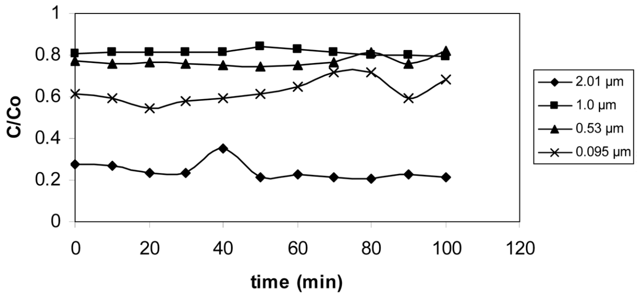


(b) Equal Surface Area

Fig. 6. Particle removal efficiencies at equal mass and equal surface area concentration under $10^{-2.5}$ M KCl (Equal mass - 0.2 mg/L; Equal surface area - 0.12 cm^2/mL).



(a) Equal Mass



(b) Equal Surface Area

Fig. 7. Particle removal efficiencies at equal mass and equal surface area concentration under 10^{-2} M KCl (Equal mass - 0.2 mg/L; Equal surface area - 0.12 cm^2/mL).

ciencies at equal mass and equal surface concentration of particles under 3 different ionic strengths. For both equal mass and equal surface area concentrations of particles, 2.01 μm particles have the highest removal (lower C/C_o value) during the transient stage of filtration. These are observed in both low and high ionic strengths. Particles of size 0.095 μm have the second highest removal during the transient stage of filtration. The least removal of 0.53 μm and 1.0 μm particles could also be observed in both equal influent mass concentration and equal influent surface area concentration of particles. The increase in the removal of particles can also be observed when ionic strength increases from 10^{-3} M KCl to 10^{-2} M KCl. When ionic strength is at 10^{-2} M KCl, a large difference in removal can be observed between 2.01 μm particles and other particles at equal influent surface area concentration of particles compared to the case of equal mass concentration of particles.

6-2. Effect of Influent Concentration on Transient Stage Efficiency

The removal efficiencies of particles are low when ionic strengths are low (10^{-3} M KCl). These can be observed in Figs. 5, 6 and 7. On the other hand, the removal of particles increases when the ionic strength increases. The removal of particles is similar at higher ionic strengths (10^{-2} M KCl and $10^{-2.5}$ M KCl). This shows that there is a critical ionic strength above which the removal of particles is not very sensitive to the increase in ionic strength. From the results, the critical ionic strength is determined to be $10^{-2.5}$ M KCl since no large variation of particles removal has been noticed although the ionic strength is increased to 10^{-2} M KCl.

The removal of 2.01 μm particles increases significantly at high ionic strength when the influent concentration increases. The removal of smaller particles increases as well with increase in influent concentration but is less prominent if compared to 2.01 μm particles. The efficiency increase might be explained by the large probability of contacts between the particles and filter grains when the concentration of particles increases. Large attractive forces were exerted on 2.01 μm particles when they contacted the filter grains. Once successfully entrained on the filter grains due to the decrease in diffuse layer thickness (at higher ionic strengths), large particles with large surface area are difficult to detach. It should be noted that the magnitude of attractive surface forces increases with the increase in surface area of particles.

6-3. Effect of Influent Concentration on Specific Surface Coverage

Specific surface coverage of collectors increases as the influent particles concentration increases (Figs. 8, 9, 10 and 11). This is significant for larger particles (2.01 μm). When the particle concentration of 2.01 μm was 0.2 mg/L, the specific surface coverage at 180 minutes of filter run was found to be around 0.0002. In contrast, significant increase of specific surface coverage was observed when the concentration of 2.01 μm particles was increased to 4.2 mg/L.

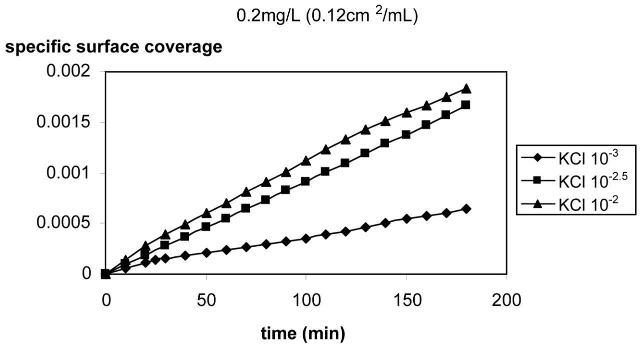
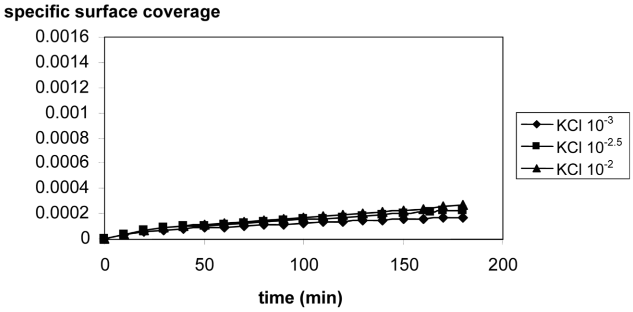
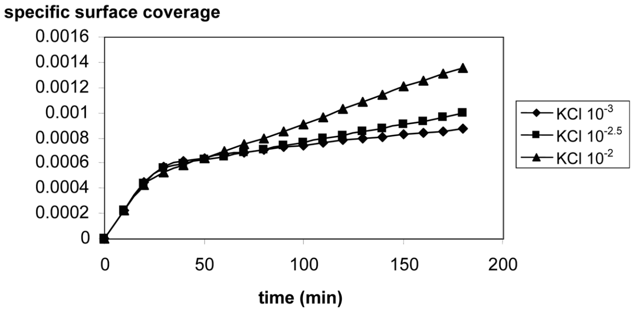


Fig. 8. Specific surface coverage of 0.095 μm particles at 0.2 mg/L (0.12 cm²/mL) concentration.

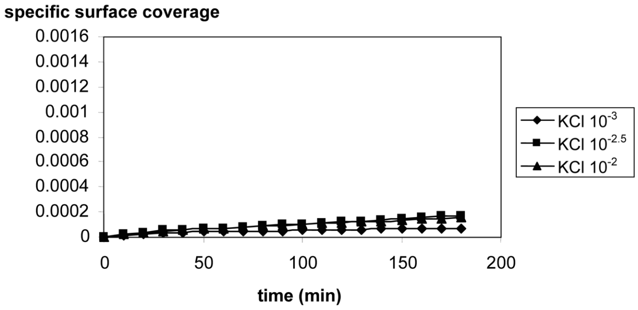


(a) 0.2mg/L (0.02cm²/mL)

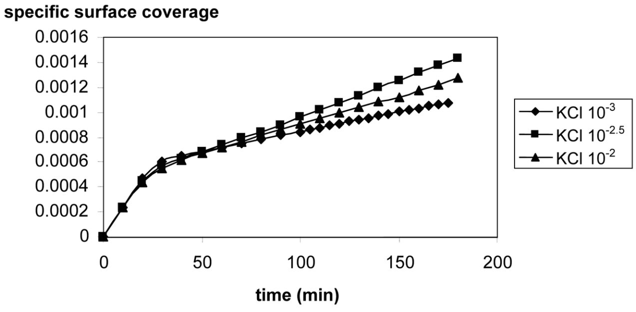


(b) 1.1mg/L (0.12cm²/mL)

Fig. 9. Specific surface coverage of 0.53 μm particles at different concentration.

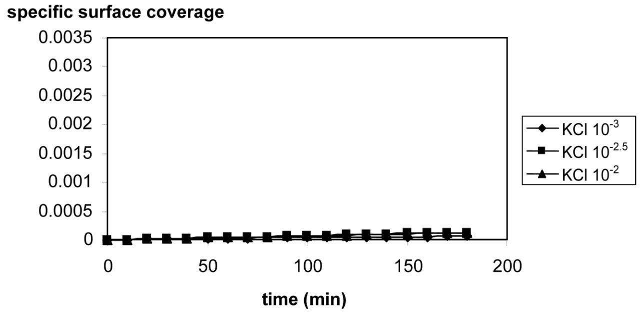


(a) 0.2mg/L (0.01cm²/mL)

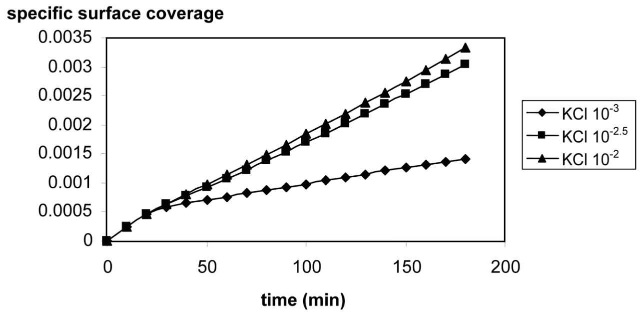


(b) 2.1mg/L (0.12cm²/mL)

Fig. 10. Specific surface coverage of 1.0 μm particles at different concentration.

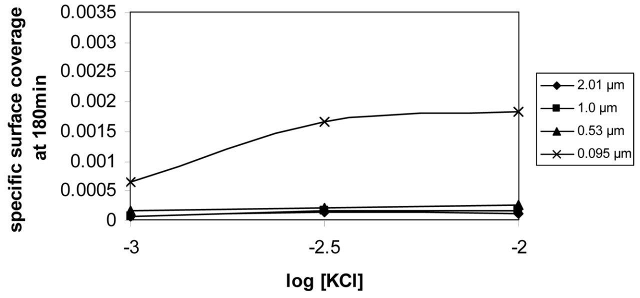


(a) 0.2mg/L (0.006cm^2/mL)

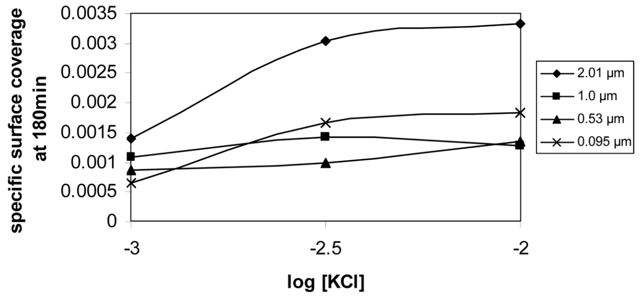


(b) 4.2mg/L (0.12cm^2/mL)

Fig. 11. Specific surface coverage of 2.01 μm particles at different concentration.



(a) Equal Mass



(b) Equal Surface Area

Fig. 12. Specific surface coverage at 180 minutes for equal mass and equal surface area concentration of particles (Equal mass - 0.2 mg/L; Equal surface area - 0.12 cm^2/mL).

The specific surface coverage for 4.2 mg/L of 2.01 μm particles at 180 minutes of filter run was found to be at least 6 times the specific coverage at 0.2 mg/L concentration. Similar variations were also noticed for different concentrations of 1.0 μm and 0.53 μm particles. When the particle concentration is high, the contact probability between particles and filter grains increases and therefore much more surface area of filter grains is covered by particles. The specific surface coverage of collectors was found to be low at low ionic strength (10^{-3} M KCl) compared to at higher ionic strengths (10^{-2} M KCl and $10^{-2.5}$ M KCl). At higher ionic strengths, the specific surface coverage assumed reasonably similar values.

6-4. Effect of Equal Mass Concentration on Specific Surface Coverage

When the mass concentration of monodispersed suspensions of 0.095 μm, 0.53 μm, 1.0 μm and 2.01 μm particles was equal, the specific surface coverage of 0.095 μm particles was larger than the specific surface coverage of 0.53 μm, 1.0 μm and 2.01 μm particles. The maximum difference between the specific surface coverages of these particles at 180 minutes was 0.0006, 0.0015 and 0.0017 at 10^{-3} M KCl, $10^{-2.5}$ M KCl and 10^{-2} M KCl, respectively. However, the specific surface coverage of 0.53 μm, 1.0 μm and 2.01 μm particles was similar at equal mass concentration where the maximum difference between specific surface coverages of these 3 particles at 180 minutes is considered very small: 0.00008, 0.00013 and 0.00017 at 10^{-3}, $10^{-2.5}$ and 10^{-2} M KCl, respectively. Generally, the maximum difference between specific surface coverage (180 min) of the particles at high ionic strength (10^{-2} and $10^{-2.5}$ M KCl) is about twice the difference at lower ionic strength (10^{-3} M KCl). In Fig. 12(a), it can also be shown that the specific surface coverage of 0.095 μm particles at 180 minutes increases significantly when ionic strength increases. This is dominant if we compare the specific surface coverage at 180 minutes of 0.095 μm particles at 10^{-3} M KCl to $10^{-2.5}$ M KCl and 10^{-2} M KCl. However, the variation of specific surface coverage of 0.53 μm, 1.0 μm and 2.01 μm particles at 180 minutes towards the change of ionic strength is less prominent if compared to the variation of 0.095 μm particles for equal mass concentration of these particles.

6-5. Effect of Equal Surface Area Concentration on Specific Surface Coverage

The specific surface coverage of 0.095 μm, 0.53 μm, 1.0 μm and 2.01 μm particles was similar during the transient stage when surface area concentration of the monodispersed suspension of these particles are equal (Fig. 12(b)). This effect occurs at low ionic strength, which is 10^{-3} M KCl where the maximum difference between specific surface coverage of these particles is only 0.00076 at 180 minutes of filter run.

Although this result seems to agree with the results observed by Jegatheesan and Vigneswaran [1997] where the specific surface coverage of particles was similar when equal surface area concentration of particles was considered, the results obtained under high ionic strength (10^{-2} M KCl and $10^{-2.5}$ M KCl) do not fully agree with their observations.

It can be observed that the maximum difference between specific surface coverage of 0.095 μm, 0.53 μm, 1.0 μm and 2.01 μm particles at higher ionic strengths (10^{-2} M KCl and $10^{-2.5}$ M KCl) was considered large, which was around 0.002 at 180 minutes. Hence, the specific surface coverage is not similar for all these particles at high ionic strength.

The specific surface coverage is not similar for all the 4 sizes of particles at high ionic strength due to the high specific surface coverage of 2.01 μm particles. In other words, the specific surface coverage is similar for smaller particles (0.095 μm, 0.53 μm and 1.0 μm) at all ionic strengths where the maximum difference between the specific surface coverage of these smaller particles is reasonably small (around 0.0007 at 180 minutes).

The effect of equal surface area concentration of particles is only dominant when particles sizes are less than or equal to 1 µm (<1 µm). There is no similarity between the specific surface coverage of 2.01 µm particles (>1 µm) and the specific surface coverage of submicron particles (0.095 µm, 0.53 µm and 1 µm) even when the surface area concentration of monodispersed suspensions of these particles is equal. This is observable at high ionic strength. However, it can be seen that there are similarities between the specific surface coverage of submicron particles (<1.0 µm) and above micron particles (>1.0 µm) at low ionic strength when the surface area concentration of these particles is equal. It should be noted that this is only observable at low ionic strength. It can also be seen from Fig. 13(b) that the increase in specific surface coverage of 0.095 µm and 2.01 µm particles at 180 minutes is sensitive to the increase of ionic strength but this increase is less prominent for 0.53 µm and 1.0 µm particles.

CONCLUSION

Monodispersed suspensions of two submicron (0.095, 0.53 µm) and a micron (1.0 µm) and one above micron (2.01 µm) polystyrene latex particles were filtered at three different ionic strengths (10^{-3}, $10^{-2.5}$ and 10^{-2} M KCl). A 5 cm filter bed with glass beads (0.1 µm diameter) as filter medium was used at a filtration velocity of 1 m/h.

1. The initial collection efficiency, η, was found to vary with particle size either at equal mass or surface area concentration of particles. When suspensions with equal mass concentrations (0.2 mg/L) or equal surface area concentrations (0.12 cm^2/mL) were filtered through the system, the largest particles exhibited higher η values. The difference between the η of largest particles and the smaller particles was prominent for suspensions with equal surface area concentrations at higher ionic strengths.
2. The collision efficiency, α, of those particles exhibits higher values at higher ionic strengths. Both at equal mass concentration and equal surface area concentration, α is only slightly dependent on particle sizes when compared to its dependence on ionic strength.
3. The specific surface coverage was similar for submicron (0.095 µm and 0.53 µm) and 1.0 µm particles during the transient stage of filtration at any ionic strength when the surface area concentrations of those suspensions were equal, which reinforces the results obtained in a previous study [Jegatheesan and Vigneswaran, 1997; Jegatheesan et al., 2005].

NOMENCLATURE

a_c, a_p : radius of filter grains (collectors) and radius of particles respectively
A_S : $2(1-p^5)/(2-3p+3p^5-2p^6)$
C_o, C : particle concentration in the influent and the effluent, respectively
d_p : particle diameter
f_o : bed porosity
g : acceleration due to gravity
H : Hamaker constant
k : Boltzmann constant
K_w : $1-1.8(\alpha')^{1/3}+\alpha'-(\alpha')^2$
L : depth of filter
N_o, N : particle number concentration in the influent and the effluent, respectively
N_A : $H/(12\pi\mu a_p^2 U)$
N_G : $[2(\rho_p-\rho_w)ga_p^2/9\mu U]$
N_{Lo} : $H/[9\pi\mu a_p^2 U]$
N_{Pe} : $2a_cU/D_\infty=[12\pi\mu a_c a_p U]/kT$
N_R : a_p/a_c
N_{vdW} : $H/(kT)$
p : $(1-f_o)^{1/3}$
t : time
T : absolute temperature of the suspension
U : approach velocity of the suspension

Greek Letters

α : collision efficiency of single-collector
α' : $(1-f_o)$
ε : permittivity of the suspension ($\varepsilon=\varepsilon_o\varepsilon_r$)
ε_o : permittivity of the vacuum
ε_r : dielectric constant of the suspension
κ : inverse Debye length
η : initial single-collector removal efficiency
η_o : initial single-collector contact efficiency
μ : dynamic viscosity of suspension
ρ_p, ρ_w: density of particles and suspension, respectively
ξ_g, ξ_p : zeta potential of filter grains and particles, respectively

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