Colloids and Surfaces B: Biointerfaces 165 (2018) 381–387

Contents lists available at ScienceDirect

Colloids and Surfaces B: Biointerfaces

journal homepage: www.elsevier.com/locate/colsurfb

Quantification of colloidal filtration of polystyrene micro-particles on glass substrate using a microfluidic device

Jianfeng Sun[a], Nil Tandogan[b], April Z Gu[c,e], Sinan Müftü[a], Edgar D Goluch[b,c,d], Kai-Tak Wan[a,*]

[a] Department of Mechanical & Industry Engineering, Northeastern University, Boston, MA 02115, USA
[b] Department of Chemical Engineering, Northeastern University, Boston, MA 02115, USA
[c] Department of Civil & Environmental Engineering, Northeastern University, Boston, MA 02115, USA
[d] Department of Biology, Northeastern University, Boston, MA 02115, USA
[e] Department of Civil and Environmental Engineering, Cornell University, Ithaca, NY, 14853, USA

ARTICLE INFO

Article history:
Received 10 November 2017
Received in revised form 31 January 2018
Accepted 19 February 2018
Available online 21 February 2018

Keywords:
Microfluidics
Filtration
Particle adhesion
DLVO

ABSTRACT

A microfluidic device was designed to investigate filtration of particles in an electrolyte in the presence of liquid flow. Polystyrene spheres in potassium chloride solution at concentrations of 3–100 mM were allowed to settle and adhere to a glass substrate. A particle free solution at the same concentration was then flushed through the microfluidic channel at 0.03–4.0 mL/h. As the hydrodynamic drag on the adhered particles exceeded the intersurface interaction with the substrate, "pull-off" occurred and the particles detached. Filtration efficiency, α, was shown to a function of both ionic concentration of the liquid medium and flow speed, consistent with a phenomenological model based on the classical DLVO theory. The results elucidates the underlying physics of filtration.

1. Introduction

Filtration is extensively used to remove microbes, colloids, and particles from polluted water. The conventional way to gauge filtration efficacy is the column test, where a particle rich solution is forced through a sand column while monitoring the number of particles retained as a function of time. Several influencing factors are identified to be ionic concentration of the solution, flowrate, temperature etc. To better assess the fate of particle transport, a celebrated model based on the underlying convection-diffusion equation is available in the literature [1,2]. Yao et al. [3] presented the classical semi-empirical colloid filtration theory (CFT), which was further substantiated by Rajagopalan [4] and Elimelech [5,6]. Other methods include subjecting the adhered particles to increasing hydrodynamic shear, and monitoring when the particles detach from the substrate [7–10]. Our earlier work demonstrated how the macroscopic filtration efficiency was related to the microscopic properties of individual bacterial cells [11,12]. The cell-substrate adhesion and elastic modulus of the cell wall were measured using atomic force microscope (AFM), and the cell geometry by optical microscope. A dimensionless Tabor's parameter comprising these intrinsic cell properties was shown to be correlated with the macroscopic filtration efficiency [11,12].

Despite the fact that classical CFT incorporates to some extent the ionic concentration and flowrate in the modeling via the convection-diffusion equation and column test, the underlying mechanism and correlation between these two factors remain unclear. Several particle trapping mechanisms operate in parallel in the traditional column test, namely, physical straining, aggregation, and surface attachment [9,13–16]. Flowrate and the subsequent hydrodynamic drag can disrupt any clogging caused by colloidal/bacterial aggregation [8,9,15,17,18] and detach the particles from the collector surface [13]. Straining and aggregation play a significant role only when the ratio of the particle diameter to the medium grain diameter is greater than 0.05 or as low as 0.002 [6,19,20]. In this paper, we design a microfluidic device to exclude the effect of straining and aggregation, but focus on particle-collector intersurface interaction and the coupled influence of flow rate and ionic concentration [9,13,14]. One advantage of such approach is the logical extension of model polystyrene particles to live bacterial cells in polluted water in the long run. Our experimental data will be analyzed based on the

* Corresponding author.
E-mail address: k.wan@northeastern.edu (K.-T. Wan).

https://doi.org/10.1016/j.colsurfb.2018.02.044
0927-7765/

classical Derjaguin-Landau-Verwey-Overbeek (DLVO) theory and rudimentary fluid mechanics, which provide practical way to assess colloidal attachment-detachment and thus filtration efficacy. Comparing with the conventional column test, another advantage of the new microfluidics presents a quick and cheap way to assess filtration.

In this paper, filtration and attachment of polystyrene particles are investigated to resemble bacterial strains as common practices in the literature [8,10,21]. The inert nonliving particles reduce the bio-complexity of living cells such as irregular volumetric and surface geometry, movement of microvilli and subsequent locomotion, buildup of cell surface substance (CSS) and extracellular matrix, specific chemical bonds to the substrate, cell division and growth etc., but nonetheless they possess the essential characteristics such as cell dimension, modifiable surface texture and chemical properties, and tunable interaction between particles and substrates.

2. Material and methods

A microfluidic channel was designed and fabricated on a quartz petri dish. A Scotch tape (3 M) was cut to a desired width and adhered to the substrate to create a master mold. Polydimethylsiloxane (PDMS) precursor was mixed at a 1:10 ratio with the curing agent (Sylgard 184; Dow Corning) and poured into the mold before vacuum was imposed to eliminate air pockets. The polymer was then cured at 69° C for 2 h. The microchannel had a cross-section of 70 μm × 3.5 mm. Three holes were drilled through the PDMS slab along the channel. Holes at either end served as inlet (Inlet-1) and outlet. The midspan inlet (Inlet-2) allowed injection of particle rich solution into the channel. The device was then sonicated, further cured in deionized water for 1 h, cleansed by isopropyl alcohol, sonicated for yet another hour, and thoroughly dried by nitrogen. Instead of plasma-activated bonding, simple thermal bonding was adopted, which was sufficient in the present study. The PDMS was gently pressed onto a glass slide to remove any air pockets, followed by baking on a hot plate at 85 °C under a small load for 2 h. Surface roughness of the glass slide was measured by atomic force microscopy to be in the range of ~10 nm. The PDMS-glass interface was sufficiently strong to meet the pressure requirement without leakage. The device was reusable after proper cleaning. Fig. 1 shows a typical device with the inlet, midspan inlet, and outlet.

The device was placed on an inverted optical microscope platform for in-situ observation. Potassium chloride solution KCl (aq) of desirable concentration ranging from $c = 3$ to 100 mM was injected into the channel via Inlet-1 using a syringe pump (model NE-300, New Era Pump System Inc., Farmingdale, NY), and exited via the outlet. Once the channel was filled, the flow halted and the liquid was stagnant. Plain polystyrene spheres (PP-30-10, Spherotech, Inc., Lake Forest, IL) with a diameter of 3.43 μm and density of 1.05 g/cm^3 were mixed with KCl (aq) at the same concentration to yield a particle number density of $\sim 7 \times 10^5$ μL^{-1}. The particles were carefully injected via inlet 2 at 0.03 mL/h. The incoming volume was carefully controlled at approximately 2–3 μL such that particles essentially reached a maximum observable extent and formed a distinct boundary at the upstream location indicated by the dashed curve in Fig. 1. The particles were allowed to settle and naturally adhere to the "collector" glass substrate, while the hydraulic pressure at the closed Inlet-2 was maintained. An optical micrograph was taken at vicinity of the particle boundary to record the initial particle distribution and areal density on the glass surface. The observation area was chosen since detached particles could only move downstream. If an area close to Inlet-2 was chosen, detached particles from the upstream would interfere with the observation. Flow from Inlet-1 at the desired flowrate, Q, from 0.03 to 4.0 mL/h then began. Fig. 2 shows micrographs taken before and after the onset of liquid flow.

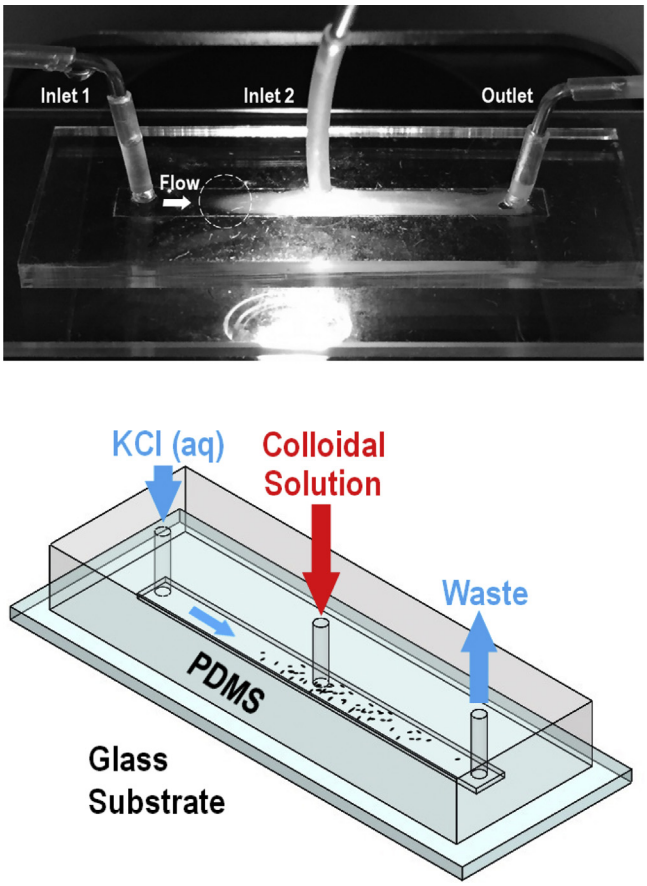

Fig. 1. The microfluidic device. The arrow indicates the flow direction of background solution. The dashed line indicates the extent particles can reach from the point of injection.

A MATLAB image processing code (version R2015b, MathWorks, Natick, MA) was written to count the particles. Optical micrographs were converted into binary images by applying a critical threshold value of grayscale to distinguish particles from the surrounding. The average number of pixels occupied by a single particle was then set as the basis to differentiate individual particles from multi-particle aggregates. For instance, if the number of pixels in a micrograph doubled that of an average single particle, it is counted as a 2-particle aggregate. Number of particles hereafter refers to the total number of retained and aggregated particles.

3. Results

The filtration or attachment efficiency, $0 \leq \alpha \leq 1$, is defined to be the fraction of retained particles such that $\alpha = 1$ when all particles are trapped and $\alpha = 0$ when all particles are detached and freely move down the channel. The time-dependent α is influenced by both c and Q, and can be expressed mathematically, $\alpha = \alpha_s(c,V,t)$, with the saturated value of $\alpha_s = \alpha(t \to \infty)$ at specific c and Q. Experiments were performed by three methods, and were repeated at least 3 times for specific combination of c and Q.

3.1. Method 1: constant flowrate

The flowrate was set at a fixed value at $t = 0$ s and held constant. Fig. 3(a) shows typical $\alpha(t)$ for $Q = 3.0$ mL/h and a range of c. As soon as the flow began, loose particles detached from the glass sur-