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Application of Colloidal Filtration Theory to Bacterial Attachment in Textile Fibrous Media

Uporaba teorije koloidne filtracije za pritrjevanje bakterij na tekstilni vlaknati medij

Abstract

A mechanism to remove *Pseudomonas* bacteria from contaminated water using textile fibrous media was proposed in this study. The attachment of *Pseudomonas* bacteria to nylon fibrous media was studied in a laboratory column experiment. A systematic study was carried out to investigate the attachment of bacteria to fibrous material as a function of media mass at a constant solution chemistry. The single-collector contact efficiency and collision efficiency from the interaction between bacteria and fibrous media were calculated applying a semi-empirical approach of clean-bed filtration theory. The experimental results indicate that removal efficiency increases with an increase in media mass up to a certain level. This is due to the change in single-collector contact efficiency and attachment/collision efficiency, as observed from experimental data regarding removal efficiency.

Keywords: textile filter, colloidal, media mass, removal efficiency, single-collector contact efficiency, collision efficiency

Povzetek

Članek se osredotoča na mehanizem za odstranjevanje bakterij Pseudomonas iz onesnažene vode s pomočjo tekstilnega vlaknatega medija. Pritrjevanje bakterij Pseudomonas na poliamidni vlaknati medij je bilo proučevano v laboratorijskem poskusu v koloni, kjer je bilo sistematično zasledovano pritrjevanje bakterij na vlaknati medij v odvisnosti od mase vlaknatega medija pri konstantni kemični sestavi raztopine. Učinkovitost stika bakterij z enojnim filtracijskim medijem in učinkovitost trkov med bakterijo ter vlaknatim medijem sta bila izračunana z uporabo polempiričnega pristopa teorije filtracije čistega sloja. Rezultati raziskave kažejo, da se učinkovitost odstranjevanja bakterij s povečanjem mase vlaknatega medija povečuje le do določene stopnje. Slednje je posledica spremembe učinkovitosti stika s filtracijskim medijem in učinkovitosti pritrjevanja/trkov, kar je tudi razvidno iz dobljenih rezultatov o učinkovitosti odstranjevanja.

Ključne besede: tekstilni filter, učinkovitost filtracije, učinkovitost stika z enojnim filtracijskim medijem, učinkovitost trčenja

1 Introduction

Microbial contaminants have been implicated in two-thirds of outbreaks of waterborne disease. Water disinfection is the removal, deactivation or killing of pathogenic microorganisms in water. Water disinfection can be carried out by either chemical and physical means, or both [1]. Although disinfection methods currently used in drinking water treatment can effectively control microbial pathogens, a research in the past few decades has revealed that a problem exists between effective disinfection and the formation of harmful disinfection by-products (DBPs) [2]. Chemical disinfectants commonly used by the water industry, such as free chlorine, chloramines and ozone, can react with various constituents in natural

water to form DBPs, many of which are carcinogens [3]. In addition, bacteria have developed chlorine-induced antibiotic resistance, meaning that a high dosage of disinfectant is required, leading to the formation of a significant amount of DBPs [4]. There is thus an urgent need to re-evaluate conventional disinfection methods and to consider some innovative approaches that enhance the reliability and robustness of disinfection, while avoiding the formation of DBPs.

In the search for alternatives, some attempts have been made by researchers, resulting in the increased use of physicochemical filtration for the removal of bacteria from potable water and wastewater because of its simplicity, high efficiency and low-costs. The attachment of bacteria to a filter surface is dictated by the adsorption mechanism, and this process does not produce by-products, such as those found in the chemical disinfection process used for water purification [5].

The use of granular filtration marked the end of waterborne epidemics in the developed world more than a century ago. However, outbreaks of waterborne diseases continue to occur at unexpectedly high levels. The major limitations of granular filters are their capacity to retain colloidal particles within pore spaces and a low filtration rate [6]. In recent years, textile materials have emerged as a substrate to be used as a filter media for the removal of colloidal particles from surface water [7]. Superior performance in the removal of colloidal particles from water can be achieved using textile fibrous media, the filtration velocities of which are 10 ten times higher than granular filter media [8].

Considerable research has been done on the effect of physical and chemical factors that control the adsorption or attachment of bacteria in the physicochemical filtration process. The attachment of bacteria to different materials in physicochemical filters depends on the media-suspension particle interaction [9]. Arnold et al. [10] evaluated the effect of cell concentration and fluid velocity on bacteria attachment in different fabric filters. They found that cell concentration and fluid velocity had no significant effect on bacteria attachment, but found that the hydrophobic nature of filter media has an effect on bacterial attachment. Jewett et al. [11] investigated the effect of the ionic strength and pH of a suspending medium on bacteria attachment in a short-column experiment containing silica spheres, and found that the attachment of bacteria was significantly affected by the ionic strength of the solution,

but that pH had no significant effect on the attachment of bacteria. Torkzaban et al. [12] studied bacteria transport through quartz sand in a column experiment. They reported that bacteria attachment not only depends on the solution chemistry, but also on the geometry of the filter media. Majumdar et al. [13] examined the effect of divalent salt and humic acid on bacteria removal through nonwoven polyester fabric. They observed an increase in the attachment of bacteria at a higher concentration of bivalent salt, but that bacterial attachment decreases in the presence of humic acid.

The above literature indicates that reported studies on bacteria filtration in column experiments found that a longer path bed containing glass bed, quartz, Ottawa sand and silica is required [14–16]. On the other hand, textile material is used primarily in the form of a fabric for bacteria filtration [17]. There are very few studies where textile fibres are used as a collector in a column experiment for bacteria filtration. Moreover, data regarding bacterial attachment behaviour on textile fibrous media as a function of media mass is limited. The specific objective of this study was to systematically examine the effects of media mass on bacterial attachment to a fibrous media surface at a constant solution chemistry of the suspending medium. The experimental observations are explained based on the colloidal filtration theory.

1.1 Filtration theory

Bacteria removal in a packed bed in a constant state can be described using the following one-dimensional filtration equation 1[18]:

$$\frac{dC}{dL} = -\frac{3}{2}\frac{(1-f)}{d_c}\eta C \tag{1},$$

where C is the bacteria concentration, L is the thickness of the filter bed, $(1 - f)$ is the solid fraction, η is the experimental single-collector contact efficiency, and d_c is the collector diameter.

Integrating over the thickness of the packed bed yield:

$$F_p = \frac{C}{C_0} = \exp\left(\frac{3(1-f)}{2d_c}L\eta\right) = \eta =$$

$$= l\eta\ F_p\left(\frac{2d_c}{3(1-f)}\right)\frac{1}{L} \tag{2},$$

where F_p is the fractional penetration and is an indicator of bathe lance between cell adsorption and desorption.

Physical factors that account for particle collisions with a porous media are incorporated into the single-collector contact efficiency, η. The single-collector contact efficiency of a single media particle or collector (η) is the ratio of the number of bacteria that collide with the collector to the number that approach a collector.

A variety of analytical solutions have been used to specify the single-collector contact efficiency for aquasol. The Yao model represents analytical solutions for determining predicted single-collector contact efficiencies based on spherical collectors that were proposed by Logan et al. [19].

$$\eta_D = 4Pe^{-2/3} \tag{3},$$

$$\eta_I = \frac{3}{2}R^2 \tag{4},$$

$$\eta_G = G \tag{5},$$

where, $\eta_{D,I}$ and η_G, represent theoretical values for the single-collector contact efficiency when the sole transport mechanisms are diffusion, interception or sedimentation, respectively.

Predicted single-collector contact efficiency calculated numerically can be approximated by the following analytical expression:

$$\eta_0 = \eta_D + \eta_I + \eta_G \tag{6}.$$

Predicted single-collector contact efficiencies are dimensionless numbers and are developed from correlations involving the following dimensionless numbers:

$$Pe = \frac{U_0 d_c}{D} \tag{7},$$

$$R = \frac{d_p}{d_c} \tag{8},$$

$$G = \frac{U_p}{U_0} \tag{9},$$

where, Pe represents the Peclet number, R and G represent the interception and gravitational numbers, U_0 and U_P represent filter approach velocity and particle settling velocity, D represents particle diffusivity, d_P represents the particle diameter and d_c represents the collector diameter.

The particle settling velocity is obtained from the formula:

$$U_p = \frac{g(p_p - p_f)d_p{}^2}{18\vartheta p_f} \tag{10},$$

where, μ and ϑ represent the dynamic and kinematic viscosity of fluid, g represents the gravitational constant, and ρ_p and ρ_f represent the particle and fluid density.

The particle diffusivity is obtained from the Stokes-Einstein equation as follows:

$$D = \frac{kT}{3\pi\eta d_p} \tag{11}$$

where, k represents Boltzmann's constant and T represents the absolute temperature.

Under conditions relevant to most aquatic systems, the experimental single-collector contact efficiency (η) is lower than the predicted single-collector contact efficiency (η_0) due to repulsive colloidal interactions between particles and collector grains [20]. The quantitative assessment of bacterial attachment to a collector surface is carried out by determining the collision efficiency (attachment) factor (α), and is often expressed as the ratio of experimental single-collector efficiency to the predicted single-collector efficiency [21].

$$\alpha = \frac{\eta}{\eta_0} \tag{12}$$

Attachment efficiency represents the fraction of collisions (contacts) between suspended particles and collector grains that result in attachment.

2 Materials and methods

For the study, 100% polyamide 6 fibres (Polyventure, Kolkata, India) of linear density 3.3 dtex and length 18 mm were used as packing material in column experiments. The microbial culture used in this study was *Pseudomonas aeruginosa* (gram-negative, rod-shaped) provided by the Department of Biotechnology, NIT Jalandhar (India). Also used were sodium hydroxide (NaOH), hydrochloric acid (HCl), sodium carbonate (Na_2CO_3), sodium chloride (NaCl) and a nutrient broth (Deejay Corporation, Jalandhar, India). All these chemicals were laboratory grade and used as received.

Sample pre-treatment
Nylon fibres were scoured with a 0.5 g/L soda ash (Na_2CO_3) solution at 60 °C for 15 minutes at a liquor ratio of 1:50 in order to remove added oils, lubricants, dust, etc. present on the fibre surface.

Bacteria culture

A liquid media was prepared for the bacteria culture by adding 1.3 g of nutrient broth to 100 mL of distilled water in a conical flux. This liquid media was kept in an autoclave for four hours at 120 °C, after which 2 mL was transferred from an active culture of *Pseudomonas aeruginosa* grown at 35 °C in a conical flux containing liquid media and incubated (Innova 42, Eppendorf, USA) at 35 °C for 18 hours. Ten mL of fresh culture was centrifuged (Centrifuge 5810 R, Eppendorf, USA) at $5000 \times g^1$, at 6 °C for 15 minutes. The resulting pellet was suspended in a phosphate buffered solution and stored at 4 °C for the column experiment.

Column experiment

The attachment of *Pseudomonas aeruginosa* was evaluated in a short-column experiment. A glass column of 10 cm in length and 5 cm in diameter (PMI, India) was packed with fibres according to the experimental design to verify the effect of media mass on microbial attachment at constant ionic strength and pH. The ionic strength and pH of the model test water were chosen on the basis of previous studies. We used 200 mL of distilled water to prepare the model test water according to the experimental plan. Sodium chloride (NaCl) was used to maintain ionic strength at 10 mM, while 0.1 M of

hydrochloric acid (HCl) and 0.1 M of sodium hydroxide (NaOH) were used to adjust the pH of the model test water to a value of 7. A fresh *Pseudomonas aeruginosa* culture was mixed with 200 mL of model test water to produce a final concentration of 8.8×10^6 cells/mL. After the packing of fibrous media, the column was flushed upward under a saturated condition with tap water for 10 minutes to ensure uniform packing and to release any trapped air bubbles. The flow was then reversed until the concentration of inlet and outlet equalised. The concentration was measured in terms of OD (optical density) using a spectrophotometer (Lambda 365, PerkinElmer). Prior to each experiment, the same pH and ionic strength as the model test water without bacteria was passed through the column to free the effluent from background contaminants in the packed fibrous media. The model test water with bacteria was passed through a fibre column, and outlet bacteria concentration was measured. The flow rate was measured as the time required to filter 200 mL of input water.

Optical density (OD) measurement

The optical density of the bacteria concentration in the inlet and outlet model test water was measured using a spectrophotometer (Lambda 365, PerkinElmer) at 600 nm.

Table 1: Parameter values used in the calculation of single-collector contact efficiency and collision efficiency

Parameter		Symbol	Media mass [g]				
			10	12	14	16	18
Media	Length [cm]	L	5.7	5.7	5.7	5.7	5.7
	Porosity	f	0.90	0.88	0.86	0.84	0.82
Bacteria/collector	Bacteria diameter [μm]	d_p	1.2	1.2	1.2	1.2	1.2
	Bacteria density [kg/m³]	ρ_p	1040	1040	1040	1040	1040
	Collector/fibre diameter [μm]	d_c	13.63	13.63	13.63	13.63	13.63
Fluid	Temperature [K]	T	293	293	293	293	293
	Density [kg/m³]	ρ	1000	1000	1000	1000	1000
	Velocity [mm/s]	U_0	3.04	2.54	2.10	1.80	1.40
	Viscosity [mNs/m²]	μ	1×10^{-3}				
	Kinematic viscosity [m²/s]	ϑ	1×10^{-6}				
Physical constants	Boltzmann constant [J/K]	K_b	1.381×10^{-23}				
	Gravity constant [m/s²]	g	9.8				

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[1] Earth's gravitational force

Calculation of single-collector contact efficiency and collision efficiency

Single-collector contact efficiency and collision efficiency were calculated from the experimental values used for the quantitative analysis of the effect of media mass on bacterial attachment. Table 1 shows the parameters used in the calculation of single-collector contact efficiency and bacterial collision (attachment) efficiencies for the column experiment. Media porosity was calculated using equations 13–15 [22].

$$Porosity = \left(1 - \frac{Media\ density}{Fiber\ density}\right) \qquad (13),$$

$$Media\ density = \left(\frac{Media\ mass}{Media\ volume}\right) \qquad (14),$$

$$Media\ volume =$$
$$= cross\ sectional\ area\ of\ media \times media\ length \qquad (15),$$

3 Results and discussion

3.1 Effect of media mass on bacteria removal efficiency

To study the effect of media mass on the bacteria removal efficiency of textile fibrous media, the model test water was passed through a column packed with fibres with various masses (i.e. 10 g, 12 g, 14 g, 16 g and 18 g). The media masses were chosen on the basis of preliminarily experimental observations. The experimental results are shown in Table 2 and Figure 1. It was found that bacteria removal efficiency increased from 30% to 63% by changing media mass from 10 g to 16 g. After that, there was

Table 2: Measured removal efficiency

Experiment	Media mass [g]	Removal efficiency $(1 - F_p)^{a)}$
1	10	30 ± 4.96 (n = 3)
2	12	47.6 ± 3.87 (n = 3)
3	14	55.6 ± 3.87 (n = 3)
4	16	63 ± 4.96 (n = 3)
5	18	65 ± 2.48 (n = 3)

a) Mean removal efficiency $(1 – F_p)$ based on
   n measurement at a 95% confidence interval.

no appreciable change in removal efficiency (65% for a mass of 18 g), suggesting that the attachment of bacteria to the media surface depends on fibre mass. The values in the table and figure represent the average values of three experiments. The incremental change in the removal efficiency of bacteria by changing the media mass was explained by calculating the single-collector contact efficiency and the attachment or collision efficiency, which is discussed in the next paragraph.
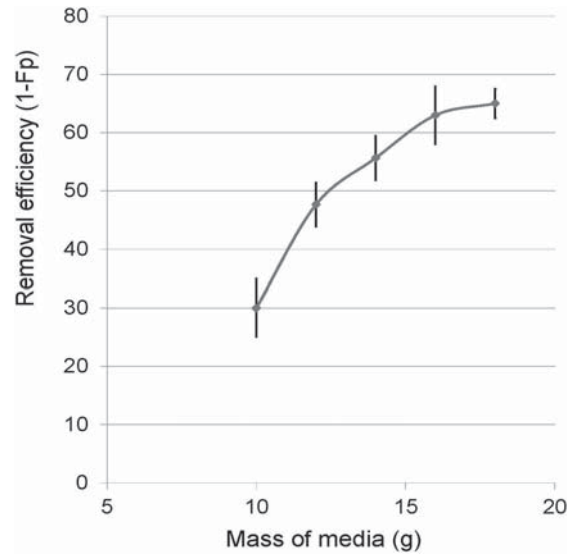

Figure 1: Removal efficiency as a function of media mass

3.2 Effect of media mass on single-collector contact efficiency and collision/ attachment efficiency

The values of single-collector contact efficiency (η) and collision (attachment) efficiency, (α) were calculated to make a quantitative comparison of removal efficiency with various media masses under identical solution conditions. Collision efficiency is defined as the ratio of the experimental single-collector contact efficiency (η) and the predicted single-collector contact efficiency (η_0). The results are presented in Table 3.

The value of α was calculated using equation 12. The values of predicted single-collector contact efficiency were calculated using equation 6 and parameter values from Table 1, while experimental single-collector contact efficiency (η) was calculated using equation 2. Attachment or collision efficiency (α) is based on n measurements at a 95% confidence interval.

Table 3: Experimental conditions, and measured single-collector contact efficiency and collision efficiency

| Experi-ment	Media mass [g]	Approach velocity [m/s]	Fraction of penetration [F_P]	Single-collector contact efficiency		Attachment or collision efficiency [α]
				Predicted [η_0]	Experi-mental [η]	
1	10	3.04×10^{-3}	0.7	7.21×10^{-3}	8.01×10^{-4}	0.111 ± 0.022 (n = 3)
2	12	2.54×10^{-3}	0.52	7.38×10^{-3}	1.22×10^{-3}	0.166 ± 0.018 (n = 3)
3	14	2.10×10^{-3}	0.44	7.59×10^{-3}	1.32×10^{-3}	0.174 ± 0.018 (n = 3)
4	16	1.80×10^{-3}	0.37	7.77×10^{-3}	1.40×10^{-3}	0.180 ± 0.024 (n = 3)
5	18	1.40×10^{-3}	0.35	8.12×10^{-3}	1.31×10^{-3}	0.161 ± 0.010 (n = 3)
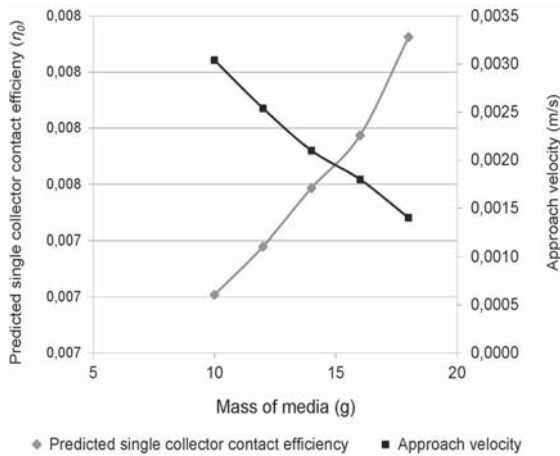
Figure 2: Effect of media mass on single-collector contact efficiency and approach velocity

It is evident from the Table 3 and Figure 2 that predicted single-collector efficiency increases from 7.21×10^{-3} to 8.12×10^{-3} by changing the media mass from 10 g to 18 g. This is due to a decrement in the approach velocity of the filtration system from 3.04×10^{-3} to 1.40×10^{-3} m/s. Enhanced single-collector contact efficiency through an increase in the media mass was therefore attributed to a change in the approach velocity of water in the filtration system. One potential explanation is that a high media mass may lead to the exposure of a higher surface area for the striking of bacteria as the result of high collector contact efficiency. When the values of the single-collector contact efficiency are higher, the probability of bacteria attaching to the surface of the fibre will be high. This was in agreement with previous studies [23], in which it was concluded that the hydrodynamic system of the filtration process plays an important role in bacterial attachment.

Collision efficiency is used for the quantitative determination of bacterial attachment to fibrous media. It is evident from Figure 3 that a change in media mass from 10 g to 16 g resulted in an increase in the collision efficiency (α) from 0.11 to 0.18, followed by a decrease to 0.16 for a media mass of 18 g.
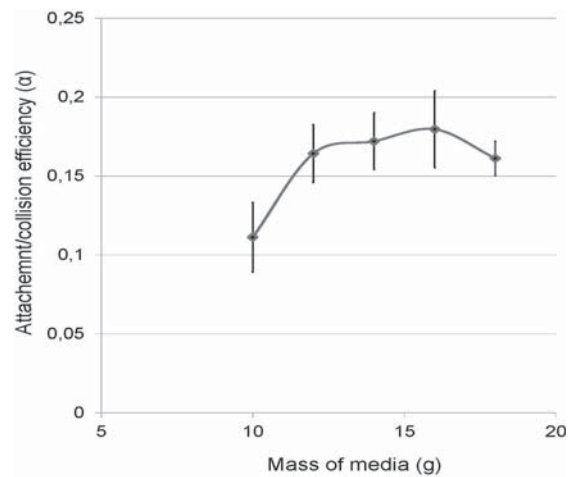

Figure 3: Collision efficiency as a function of media mass

The value of collision efficiency at 16 g was 0.18 and resulted in a removal efficiency of 63%. A further increment in mass did not result in any appreciable change in removal efficiency. This can be attributed to the decrement in collision efficiency as observed.

4 Conclusion

It is important to understand the effect of physical factors on the performance of filters designed to remove microbial pathogens from surface water. An

attempt was made to link an important factor of the textile porous media to enhance the removal efficiency of bacterial cells. Experimental evidence demonstrated that media mass can play an important role in bacterial removal and attachment. In this study, a filter media with various masses was selected for the experiment at a constant solution chemistry. Bacteria attachment and removal efficiency increased with an increase in media mass up to a certain level. According to colloidal filtration theory, this is possibly due to a change in the single-collector contact efficiency and collision (attachment) efficiency of the fibrous media.

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