*Desalination and Water Treatment*
www.deswater.com

11 (2009) 98–108



# Estimating progress of specific deposit in a dual-media BOPS-sand water filter using a matrix approach

Ahmad Jusoh[a,*], A. G. Halim[b], A. Nora'aini[a], W. B. Wan Nik[c], E. Azizah[d]

[a]*Department of Engineering Science, Faculty of Science and Technology*
*Tel. +609 6683344; Fax. +609 6696440; email: ahmadj@umt.edu.my*
[b]*Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*
[c]*Department of Maritime Technology, Faculty of Maritime Studies and Marine Sciences, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia*
[d]*Faculty of Innovative Design and Technology, University Darul Iman Malaysia, 21030 Kuala Terengganu, Malaysia*

Received 31 March 2009; Accepted 31 August 2009

ABSTRACT

A new matrix approach which incorporated Rajagopalan and Tien model was developed to simulate the progress of sediment deposition in sublayers of filtration media for mono-media sand and BOPS filters as well as dual-media BOPS-sand filters, at different time until the end of filtration process. The results of specific deposit in the matrix form can be used later to predict the operational head loss in the sublayers of filter at different time. The experiment on filtration process using a filter column was carried out to treat raw water at typical rapid filtration flow rate of 3 to 7.5 m/h. The influent and effluent water turbidity, total suspended solids and the operational head loss at specific thickness and time were monitored and recorded during filtration process. A dual-media filter of BOPS-sand with ES of 0.8:0.5 mm to 1.0:0.5 mm are effective in treating raw water and produce high quality effluent turbidity as good as the conventional mono-media sand filter.

***Keywords:*** Specific deposit; Dual-media BOPS-sand filter; Matrix approach

## 1. Introduction

Filtration is a process commonly used for the removal of particulate matter in water and wastewater treatment. Granular filter media has been found effective for removing particulate of a wide range of sizes up to 50 µm (Osmak et al., 1997) that readily exist in water. Most surface waters contain microorganism such as algae, viruses, pathogens, sediment, clay, colloidal humic compound and other organic and inorganic particulate matter.

The design and operation of filters are still depending on empirical basis. Even though much progress has been made in the aspect of filtration modelling, as yet no reliable and comprehensive applicable models of the filtration process have been developed. In filtration, the progress in deposition of suspended particles within a filter increases with time and alters the structure of the filter media as well as the nature of the surface interactions between particles and the collecting media. It creates a complex geometry of the pores changes as deposition build up. More over, the attachment process is dependent upon the interaction forces condition, contributed by the charge of the particles, filter grains and ionic chemicals being used in the influent. Therefore, the collection efficiency and the permeability of the media change with time.

There are several researchers familiarize trajectory model approach to modelling deep-bed filter and evaluated using colloid filtration theory (CFT), among them include Yao et al. (1971), Rajagopalan and Tien (1976) and Tufenkji and Elimelech (2004). Yao et al theory is based on

*Corresponding author.

*Presented at CESE-2009, Challenges in Environmental Science & Engineering, 14–17 July, 2009, Townsville, Queensland, Australia.*

doi: 10.5004/dwt.2009.8[illegible]

the accumulation of particles on a single collector filter grain (that is incorporated into a mass balance through a filter). However, Yao filtration model under predicts the number collisions between suspended particles and grains collectors as compared to experimental results. Rajagopalan and Tien developed the model based on sphere-in-cell model, included additional attractive forces due to London-van der waals forces between the grains collectors and suspended particles and considered for reduced collisions due to viscous resistance of the water between the particle and grains collector. The recent model developed by Tufenkji and Elimelech was also considered a close range forces, including hydrodynamic interaction and universal van der waals attractive forces.

The transport of suspended or colloidal particles from the fluid to a filter grain collector is typically dominated by three mechanisms: diffusion, interception and sedimentation. Smaller particles (<1 μm, Lin et al., 2008) are influenced by Brownian motion, deviated from the fluid streamlines due to diffusion. Particles pass the grains collector surface by a distance of half the particle diameter or less possibly will contact and intercept to the collector. Particles with a high density greater than water tend to deviate from fluids streamlines due to gravitational forces. Therefore, the total of these three processes act as the basis of the single collector efficiency (Yao et al., 1971):

$$\eta_{\text{total}} = \eta_D + \eta_I + \eta_S = 0.9\left(\frac{kT}{\mu d_P d_C V}\right)^{2/3} + \frac{3}{2}\left(\frac{d_P}{d_C}\right)^2 + \frac{(\rho_S - \rho_W) g d_P^{\,2}}{18\mu V} \quad (1)$$

where $\eta_D$, $\eta_I$, $\eta_S$ are transport efficiencies due to diffusion, interception and sedimentation, $T$ is absolute temperature, μ is dynamic viscosity of water, $d_p$ is average diameter of kaolin clay particles, $d_c$ *is* average diameter of grain media, $\rho_S$ is density of suspended particles, $\rho_W$ is density of water, $g$ is gravity and $V$ is superficial filtration velocity.

Nowadays, due to an extensive development that contributes to high turbid water as well as high water demand, sand filter alone is not efficient enough in producing a high filtration capacity. Therefore, a design strategy is the most important in selection of a dual-media filter such as burned oil palm shell (BOPS) and sand. The analysis of the filter performance in terms of efficiency and coefficient of filtration, suspended solid removal, development of sediment deposit and operation filtration time are the main objective of this research.

## 2. Material and methods

Burned oil palm shell (BOPS) was prepared from oil palm fruit shell which is a solid waste by-product from oil palm factory and abundantly available in Malaysia. Palm shells were burned in a furnace at about 300°C and then ground into granules. They were sieved to establish particles size distribution curve. BOPS granules are lighter and porous with low specific gravity of 1.25–1.35, with an average of 1.30. The shape of BOPS granules prepared by crushing is angular with spherecity of 0.7 and initial porosity of about 0.49.

The determination of BOPS effective sizes (ES) at 0.6, 0.8 and 1.0 mm and uniformity coefficient (UC) of 1.5 are shown in Fig. 1. Sand media which is readily available in the local market was also sieved to produce the size dis-

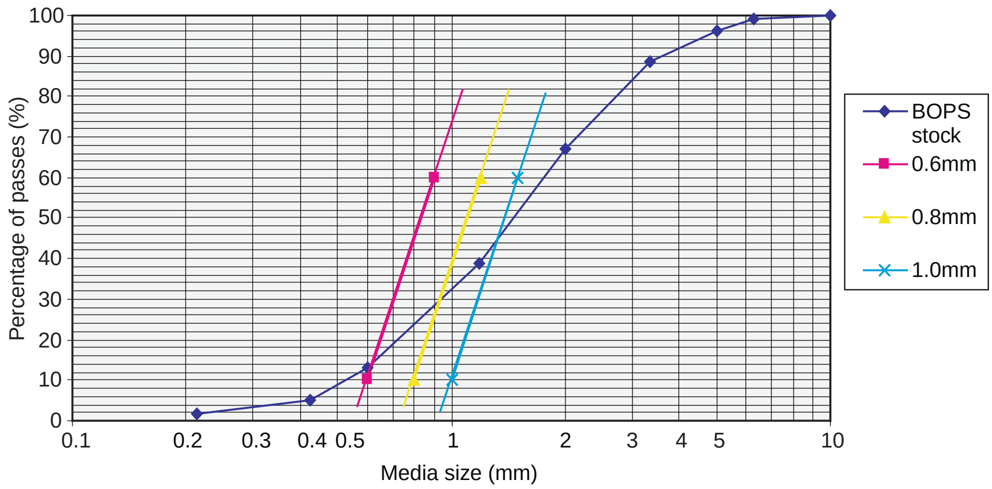


Fig. 1. Determination of effective sizes of BOPS at ES = 0.6, 0.8 and 1.0 mm and UC = 1.5.

tribution curve in order to determine the effective size of 0.5 mm and uniformity coefficient of 1.5 in the same manner as the BOPS media. Based on Fig. 1 the size limit (i.e., the smallest and the largest size) could be established as illustrated in Table 1.

Raw water was prepared by adding kaolin clay powder into tap water for specified concentration in the range of 70–80 mg/L. The filtration process was run using a filter column equipped with manometer tubes to monitor and record the head losses at various time intervals and depths of filter media as shown in Fig. 2. On top of that, influent and effluent water turbidity as well as the total suspended solids (TSS) concentration at two filtration flow rates of 3.62 and 5.81 m/h was monitored to analyse the performance of mono-media BOPS, sand and dual-media filter of BOPS and sand. These flow rates were within the range of rapid filtration rate of 3–7.5 m/h (Kawamura, 2000). The filter was backwashed when the filtration process indicated a negative pressure (i.e., the appearance of air bubble).

As a new filter media, the appropriateness in terms of effective sizes, uniformity coefficient and the best combination of BOPS and sand sizes in dual-media filter were primarily very important to be established before a design protocol or guideline could be recommended.

Table 1
The size limit for sand and BOPS media.

| Effective size, ES UC = 1.5 | Smallest size | | Largest size | |
|---|---|---|---|---|
| | $P_{10} - 0.2\,(P_{60} - P_{10})$ | | $P_{60} + 0.8\,(P_{60} - P_{10})$ | |
| Sand | % | Size (mm) | % | Size (mm) |
| 0.5 mm | 15.2 | 0.45 | 43.2 | 0.95 |
| BOPS | | | | |
| 0.6 mm | 8.20 | 0.50 | 41.20 | 1.20 |
| 0.8 mm | 20.8 | 0.75 | 52.80 | 1.50 |
| 1.0 mm | 28.0 | 0.90 | 36.00 | 2.00 |

## 3. Results and discussion

### 3.1. Modelling approach

#### *3.1.1. Determination of efficiency and coefficient of filtration and TSS removal by a trajectory approach*

As a clean media filtration, this study applies the trajectory approach developed by Rajagopalan and

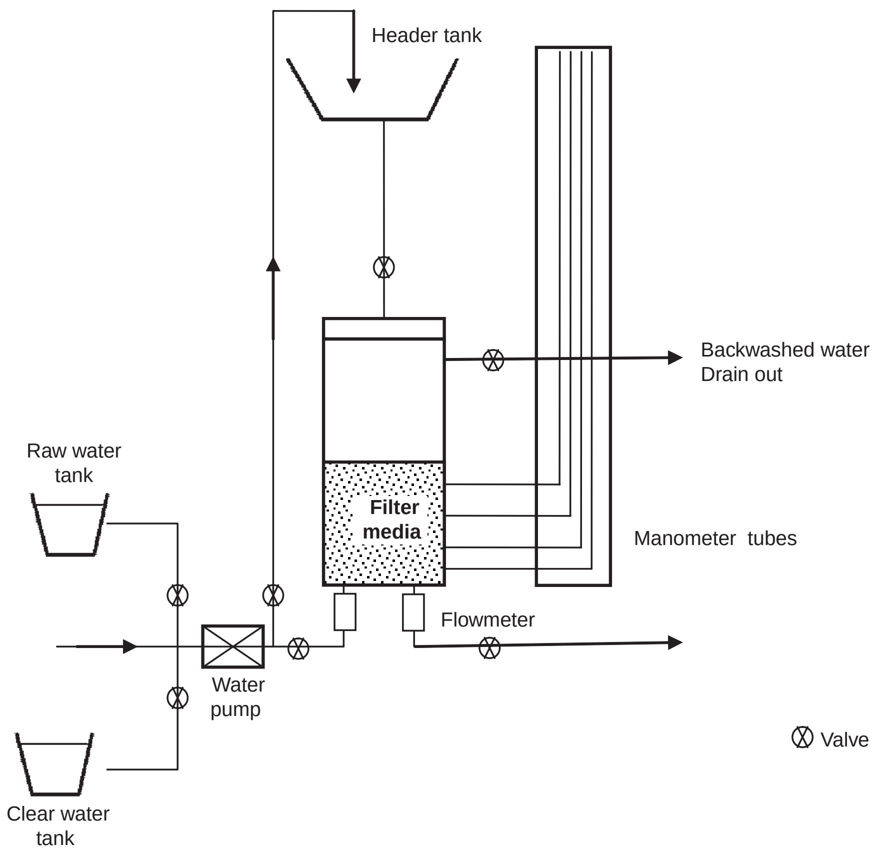


Fig. 2. A schematic diagram of a filtration system equipped with manometer.

Tien (1976) or known as RT model. The RT model is similar to Yao filtration model, where the total filtration efficiency is including three filtration mechanism processes, i.e., diffusion, interception and sedimentation as shown in Eq. (2):

$$\eta_{\text{total}} = 4A_S^{1/3}Pe^{-2/3} + A_S N_{LO}{}^{1/8} N_R{}^{15/8} + 3.38\times10^{-3} A_S \eta_S{}^{1.2} N_R{}^{-0.4} \quad (2)$$

where $A_S$ and $\gamma$ is porosity function, $N_{LO}$ is London group, *Pe* is peclet number, and $N_R$ is relative size group which are given in detail in the Appendix.

Begin with Yao et al. (1971) theory on the accumulation of suspended particles on a single filter grain collector and incorporated with a mass balance of the flux flow through a filter unit the differential Equation is shown as Eq. (3). The effluent concentration passing through a sublayer of filter ($\Delta L$) can be determined by integrating Eq. (3) and as produced by Eq. (5):

$$\frac{dC}{dz} = \frac{-3(1-\varepsilon)\eta\alpha C}{2dc} \quad (3)$$

$$\lambda = \frac{3(1-\varepsilon)\eta\alpha}{2dc} \quad (4)$$

$$C_e = C_o \exp\left[\frac{-3(1-\varepsilon)\eta\alpha\,\Delta L}{2dc}\right] \quad (5)$$

where $\eta$ *is* transport efficiency, $\alpha$ is attachment coefficient, *C* is concentration of suspended solids, *dc* is average diameter of grain media, $C_e$ is effluent concentration of suspended solids and $C_o$ is influent concentration of suspended solids.

In order to determine the performance of mono-media BOPS and sand filter, the most important parameter such as efficiency, $\eta$, coefficient of filtration, $\lambda$ and suspended solids removal $(C_o - C_e)/C_o$ should be analysed. Several assumptions should be made prior to solve Eqs. (2, 4 and 5). The average size and density of kaolin clay particles were assumed to be constant, 10 μm and 2200 kg/m$^3$, respectively (Montgomery. 1985; Dhamappa et al. 1997). Due to kaolin clay particles and the outer layer of filter media, are both have negative charges, the possibility of clay particles to adhere on the filter media or so-called "attachment efficiency" or $\alpha$, might be quite low (repulsive mode). Therefore, $\alpha$ was assumed in the ranged of 0.1 to 0.2 (or 10 to 20%, Lin, et al., 2008).

The performance of mono-media BOPS of effective size, ES = 0.6, 0.8 and 1.0 mm and sand of ES = 0.5 mm was then calculated at $\Delta L$ = 0.1 m depth of filter and different sizes of media are shown in Table 2. From Table 2, the mono-media of sand filter with a smaller porosity and ES (as compared to BOPS) has the highest efficiency and coefficient of filtration as well as percentage of total suspended solids (TSS) removal. In the case of mono-media BOPS, the higher the ES (or average size of BOPS media), produce the lower coefficient of filtration and the percentage of TSS removal as shown in Table 2.

Table 2
The efficiency and coefficient of filtration as well as suspended solid removal at different size of media and velocities for 0.1 m depth and particle size of 10 μm.

| Sand (mm) | *V* (m/h) | Grain size *dc* (m) | Initial porosity $\varepsilon_o$ | Filtration efficiency $\eta$ | Filtration coefficient $\lambda$ | $(C_o - C_e)/C_o$ |
|---|---|---|---|---|---|---|
| ES = 0.5 | 3.62 | 0.0005 | 0.40 | 0.04080 | 15.50 | 0.787 |
| | | 0.0006 | 0.40 | 0.04100 | 13.00 | 0.727 |
| | 5.81 | 0.0005 | 0.40 | 0.02600 | 9.88 | 0.628 |
| | | 0.0006 | 0.40 | 0.02550 | 8.01 | 0.551 |
| BOPS | | | | | | |
| ES = 0.6 | 3.62 | 0.0005 | 0.49 | 0.01980 | 6.07 | 0.455 |
| | | 0.0006 | 0.49 | 0.01990 | 5.09 | 0.399 |
| | 5.81 | 0.0005 | 0.49 | 0.01260 | 3.86 | 0.320 |
| | | 0.0006 | 0.49 | 0.01230 | 3.12 | 0.268 |
| ES = 0.8 | 3.62 | 0.0008 | 0.49 | 0.00240 | 5.05 | 0.396 |
| | | 0.0009 | 0.49 | 0.00210 | 4.63 | 0.371 |
| | 5.81 | 0.0008 | 0.49 | 0.01245 | 2.36 | 0.211 |
| | | 0.0009 | 0.49 | 0.01260 | 2.14 | 0.193 |
| ES = 1.0 | 3.62 | 0.0010 | 0.49 | 0.02810 | 4.30 | 0.350 |
| | | 0.0011 | 0.49 | 0.02900 | 4.03 | 0.332 |
| | 5.81 | 0.0010 | 0.49 | 0.01290 | 1.97 | 0.179 |
| | | 0.0011 | 0.49 | 0.01320 | 1.83 | 0.167 |

This phenomenon is clearly indicated by Eqs. (4 and 5) whereby coefficient of filtration and percentage of TSS are inversely proportionate to the size of media. Qi (1998) and Kim and Whittle (2006) obtained the same results that the coefficient of filtration or the performance of a filter reduced as the size of media increases. Furthermore, all filters depicted that the increase of filtration flow rate resulted in lower coefficient of filtration and percentage of TSS removal (Table 2). The higher the flow rate or velocity means that the shorter the opportunity time for the filtration process and this phenomenon contributes to the lower coefficient of filtration as well as percentage of TSS removal. William et al. (2007) also found that the TSS removal efficiency was reduced when filtration velocity was increased from 12.2 to 24.4 m/h.

### *3.1.2. Development of specific deposit in a filter by phenomenological approach*

The development of specific deposit during filtration process by phenomenological approach began with Iwasaki (1937) and followed by several other researchers such as Mackie and Bai (1992) and Mackie and Zhao (1999). The progress of specific deposit is dependence on both, the filter thickness and filtration time as shown in Eq. (6):

$$V\frac{\partial C}{\partial z}+\frac{\partial \sigma}{\partial t}=0 \tag{6}$$

where $V$ is superficial filtration velocity, $C$ is concentration of suspended solids, σ is specific deposit, $z$ is media thickness and $t$ is time.

According to Bai and Tien (2000) and Altoe et al. (2006), the kinetic of sediment deposit in a filter is functions of suspended solids concentration and filtration velocity or as first-order particle retention kinetic is shown in Eq. (7) as follows:

$$\frac{\partial \sigma}{\partial t}=\lambda V C \tag{7}$$

where $\sigma$ is specific deposit, $t$ is time, $\lambda$ is filter coefficient, $V$ is Superficial filtration velocity and $C$ is concentration of suspended solids.

The initial boundary conditions for a medium initially without deposition are

$$\begin{aligned} &C=C_o && (z=0)\\ &C=0,\ \sigma=0 && (z>0.\ t=0) \end{aligned} \tag{8}$$

where $C$ is concentration of suspended solids, $Co$ is influent concentration of suspended solids, $z$ is media thickness, σ is specific deposit and $t$ is time.

Integrating Eqs. (6 and 7) from initial boundary condition to the final boundary conditions of $C = C_o$, $t = \Delta t$ and $z = \Delta L$.

The experimental data for the concentration of TSS (kaolin clay) were recorded in mg/L and specific deposit or deposited sediment, also can be calculated as in mg/L. However, it is more useful to express the specific deposit in terms of volume of sediment per volume of filter media or v/v since it could relate the sediment volume to the current porosity value at specified time of filtration process. Therefore, the conversion unit from *gram* to cubic centimetres can be determined by using Eq. (9) (Montgomery, 1985). According to Tobiason and Vigneswaran (1994) the porosity of sediment may vary from 60 to 80%:

$$\frac{\sigma''}{\sigma'}=\frac{1/\rho_W-1/\rho_S}{(\rho_S/\rho_W-1)(1-\varepsilon_D)} \tag{9}$$

where σ″/σ′ is cubic centimetre per gram, $\rho_W$ is density of water, $\rho_S$ is density of suspended particles and $\varepsilon_D$ is porosity of sediment.

Using Eq. (9) it is found that one gram of sediment is equal to 1.3 $cm^3$ by assuming 65% porosity of sediment and the typical average water temperature for Malaysia of $25^o$ C. This value suits with the value recommended by Ojha and Graham (1993) which is in the range of 0.4–19.0 $cm^3$ for one gram of sediment. Tobiason and Vigneswaran (1994) proposed that the maximum capacity of sediment volume should be less than the original porosity of filter media, i.e. $\sigma_t$ max < $\varepsilon_o$.

### *3.1.3. A new matrix approach*

Since the head losses recorded at different points within the filter layer thickness and time interval contribute towards the final results in the form of a matrix, the accumulation of deposited sediment in different sublayers and at different time should be linked to head loss data (matrix form) in order to predict head loss using the simulated deposited sediment data. There are several assumptions made in the matrix approach:

a) The first sublayer covers the distance (or thickness) from the surface of filter media to the first manometer position. The second, third and subsequent sublayers cover the distance from the first to second manometer, from the second to the third manometer and so on respectively, until the last sublayer.
b) An average size for the sublayers is determined based on number of sublayers and the size limit (from smallest to the largest) for the selected filter media and effective size.
c) The filtration process begins at the influent concentration, $Co_1$ and after passing the first sublayer, it will produce the effluent, $Ce_1$. The effluent from the first sublayer becomes the influent to the second sublayer, $Co_2$ ($Ce_1 = Co_2$) and after passing the second sublayer,

it will produce the effluent, $Ce_2$. Thereafter similar filtration process is repeated from one sublayer to another until the last sublayer of the filter media.

d) The porosity is assumed to be constant for all the sublayers of filter media at a specific time (i.e., $\varepsilon_t = \varepsilon_o - \sigma_t$). The value of $\sigma_t$ can be determined by using Eq. (7).

e) The development of deposited sediment is directly proportional to time as indicated by Eq. (7) as well as by the experimental data and simulated results as illustrated in Figs. 3 (a) and (b). Both these figures indicated that the relationship of deposited sediment with time is closely related (i.e., $R^2 = 0.96 - 1.0$).

The accumulation of deposited sediment in the first sublayer, second sublayer and until the 5th sublayer at time $t_2$ (time $t_1$ is considered as zero) is illustrated as follows:

$$\sigma_{21} = \sigma_{11} + \Delta\sigma_{t2\,L1}$$
$$\sigma_{22} = \sigma_{21} + \Delta\sigma_{t2\,L2}$$
$$\sigma_{23} = \sigma_{22} + \Delta\sigma_{t2\,L3}$$
$$\sigma_{24} = \sigma_{23} + \Delta\sigma_{t2\,L4}$$
$$\sigma_{25} = \sigma_{24} + \Delta\sigma_{t2\,L5}$$

The accumulation of deposited sediment in all sublayers and at time $t_3$ is described as follows:

$$\sigma_{31} = \sigma_{21} + \Delta\sigma_{t3\,L1}$$
$$\sigma_{32} = \sigma_{22} + \Delta\sigma_{t3\,L1} + \Delta\sigma_{t3\,L2}$$
$$\sigma_{33} = \sigma_{23} + \Delta\sigma_{t3\,L1} + \Delta\sigma_{t3\,L2} + \Delta\sigma_{t3\,L3}$$
$$\sigma_{34} = \sigma_{24} + \Delta\sigma_{t3\,L1} + \Delta\sigma_{t3\,L2} + \Delta\sigma_{t3\,L3} + \Delta\sigma_{t3\,L4}$$
$$\sigma_{35} = \sigma_{25} + \Delta\sigma_{t3\,L1} + \Delta\sigma_{t3\,L2} + \Delta\sigma_{t3\,L3} + \Delta\sigma_{t3\,L4} + \Delta\sigma_{t3\,L5}$$

Therefore, the accumulation of sediment in all sublayers and at time $t_1$ until the final time followed the same procedures to form a normal matrix representation. The example of simulated results using above procedures for a dual-media filter of BOPS-sand with ES = 1.0:0.5 mm and at filtration velocity of 5.81 m/h are shown in Table 3. Table 3 also indicates that the dual-media BOPS-sand filter has a total depth of 38 cm with BOPS (ES = 1.0 mm) 25.3 cm thick located at the top layer overlaying the sand (ES = 0.5 mm)12.7 cm thick at the bottom. There are six sublayers of BOPS and three sublayers of sand which have different thickness as shown in Table 3.

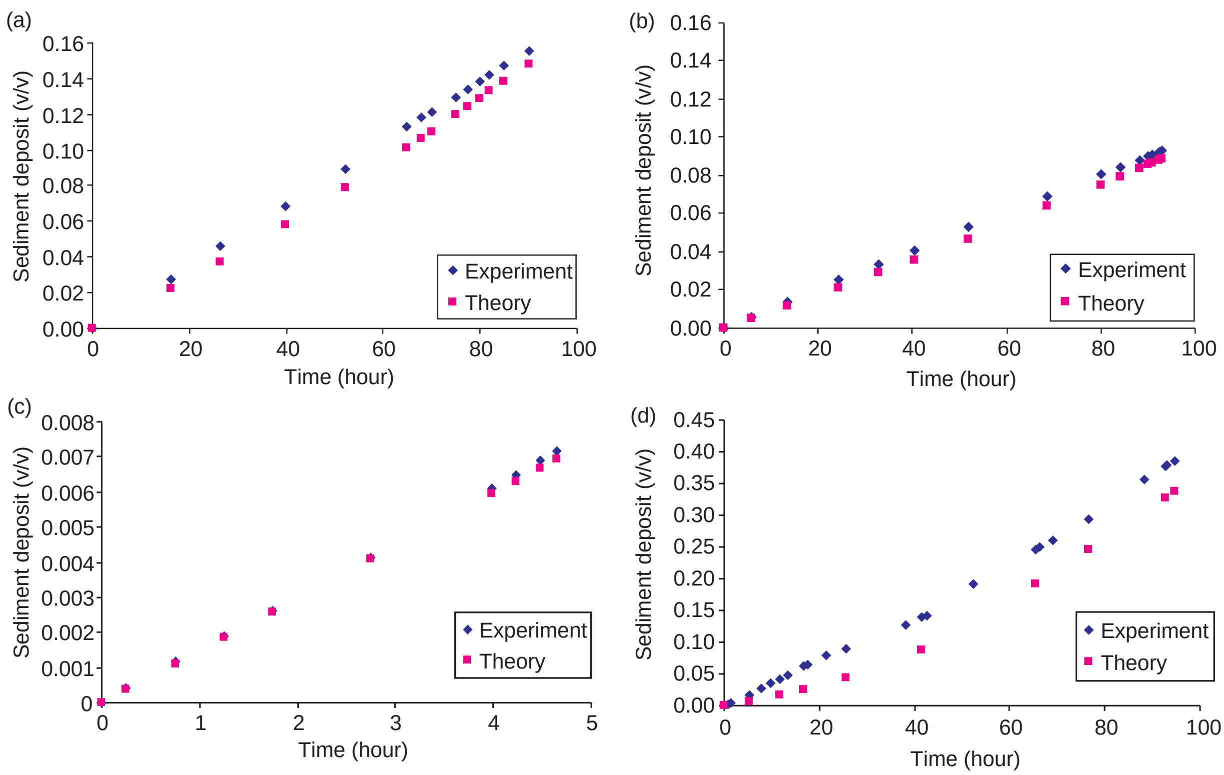


Fig. 3. A progress of the accumulated sediment of the total sublayers for dual-media filter of BOPS-sand, mono-media filter of sand and mono-media filter of BOPS.
(a) Dual-media filter of BOPS-sand at $V = 5.81$ m/h.
(b) Dual-media filter of BOPS-sand at $V = 3.62$ m/h.
(c) mono-media filter of sand at $V = 5.81$ m/h.
(d) mono-media filter of BOPS at $V = 5.81$ m/h.

Table 3
A sample of simulated results of deposited sediment at various sublayers and times for a dual-media filter BOPS-sand.

| Time (hour) | σ (v/v) (Dual-media ES = 1.0 mm: 0.5 mm, V = 5.81 m/h) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | (2 cm) | (5 cm) | (8 cm) | (13 cm) | (18 cm) | (25.3 cm) | (28 cm) | (33 cm) | (38 cm) |
| 0.00 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 16.25 | 0.0008 | 0.0018 | 0.0028 | 0.0041 | 0.0052 | 0.0066 | 0.0122 | 0.0177 | 0.0208 |
| 26.50 | 0.0013 | 0.0031 | 0.0047 | 0.0070 | 0.0089 | 0.0113 | 0.0208 | 0.0299 | 0.0349 |
| 39.70 | 0.0021 | 0.0051 | 0.0077 | 0.0113 | 0.0144 | 0.0183 | 0.0334 | 0.0473 | 0.0547 |
| 52.12 | 0.0031 | 0.0072 | 0.0109 | 0.0161 | 0.0204 | 0.0258 | 0.0466 | 0.0651 | 0.0747 |
| 64.95 | 0.0042 | 0.0099 | 0.0149 | 0.0218 | 0.0276 | 0.0348 | 0.0620 | 0.0852 | 0.0967 |
| 67.78 | 0.0044 | 0.0105 | 0.0158 | 0.0231 | 0.0293 | 0.0369 | 0.0655 | 0.0897 | 0.1016 |
| 70.00 | 0.0047 | 0.0111 | 0.0167 | 0.0243 | 0.0307 | 0.0387 | 0.0686 | 0.0935 | 0.1056 |
| 75.00 | 0.0052 | 0.0124 | 0.0186 | 0.0271 | 0.0342 | 0.0430 | 0.0756 | 0.1021 | 0.1147 |
| 77.50 | 0.0055 | 0.0131 | 0.0196 | 0.0286 | 0.0360 | 0.0452 | 0.0792 | 0.1065 | 0.1193 |
| 80.00 | 0.0059 | 0.0138 | 0.0207 | 0.0301 | 0.0379 | 0.0475 | 0.0829 | 0.1109 | 0.1240 |
| 82.00 | 0.0061 | 0.0144 | 0.0216 | 0.0313 | 0.0394 | 0.0493 | 0.0858 | 0.1144 | 0.1277 |

The progress of sediment accumulated after passing through all sublayers (the whole filter media) as the time increases is illustrated by the last column of Table 3. This progress of simulated value of sediment accumulated can be verified by comparing with the corresponding experimental data which is given in Fig. 3. The progress of the experimental sediment deposit for the whole media (i.e., up to the last sublayer) was obtained by multiplying the specified flow rate with the differences of measured influent and effluent concentration as well as with the filtration progressing time. It was found that the simulated results were very close to the experimental data, which are indicated by small values of the root mean square error (RMSE) for the dual-media filter BOPS-sand ES = 0.6:0.5 mm, ES = 0.8:0.5 mm and ES = 1.0:0.5 mm at filtration velocity of 5.81 m/h, i.e., 0.00256, 0.00615 and 0.00968, respectively. Furthermore, the correlation $R^2$ between the simulated results and experimental data of the accumulated sediment for the selected dual-media filter mentioned are all very close to one (about 0.99).

From Fig. 3, the rate of accumulated sediment received by the dual-media BOPS-sand is higher for the higher flow rates, which are 0.00156 and 0.00098 v/v per hour at 5.81 and 3.62 m/h respectively. This phenomenon is in accordance with Eq. (7) that shows the rate of accumulated sediment is proportional to the filtration velocity.

As for the comparison, in the case of mono-media sand alone the total capacity of sediment deposit is very low, that is just 0.0075 v/v with a shorter filtration running time of less than 5 h. (at filtration velocity of 5.81 m/h) as shown in Fig. 3 (c). Whereas, in the case of mono-media BOPS, the total capacity of sediment deposit is very much higher, that is 0.35 v/v with a longer filtration running time achieved almost 100 h. as shown in Fig. 3 (d) at the same filtration velocity of 5.81 m/h. This is due to the BOPS media is more porous than the sand and could receive a higher capacity of sediment deposit.

The quantity of sediment for each sublayer and for all sublayers at the final filtration time (present as cross-sectional view at each point of Fig 3) can be visualized and presented in bar diagram as shown in Fig. 4. From this Fig. the quantity of sediment deposited whether as a net or cumulative value as well as their percentage at each sublayer can be identified and clearly shown. Based on Fig. 4 the total capacity in terms of sediment deposited volume of dual media filter of BOPS-sand ES = 0.6:0.5 mm, ES = 0.8:0.5 mm and ES = 1.0:0.5 mm increases from 0.057 v/v to 0.076 v/v and up to 0.128 v/v as the effective sizes of BOPS upper media increases (i.e., ES = 0.6, 0.8 and 1.0 mm). This means that a higher effective size of BOPS has a higher void volume (higher reservoir capacity) in order to contain a larger volume of deposited sediment.

On top of that, as the effective size of BOPS increases, the percentage of deposited sediment in the BOPS layer decreases (however, the quantity of deposited sediment in terms of volume, v/v still increases). The decreasing order is due to the increasing amount of this deposited sediment that penetrated through the BOPS layer and received by the sand layer underneath. This increasing phenomenon of deposited sediment (as effective size of BOPS increases) in the sand layer is shown by both Figs. 4 and 5.

For instance, the percentage of deposited sediment in BOPS layer for the dual-media BOPS-sand with ES = 0.6:0.5 mm are 61% (or 0.036 v/v) and 74% (or 0.034 v/v) at filtration velocity of 5.81 and 3.62 m/h respectively. While the percentage of sediment deposited in BOPS layer for the dual-media BOPS-sand with

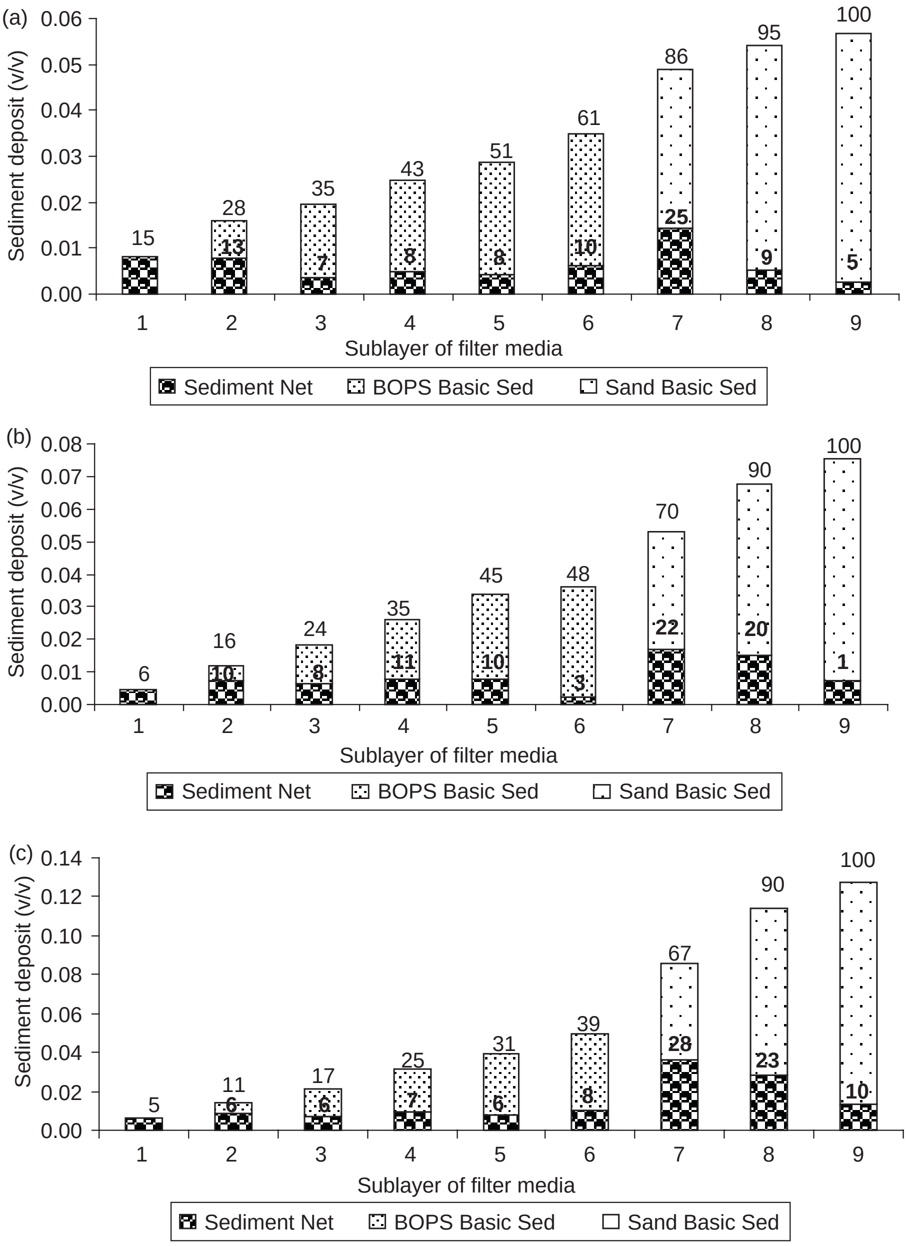


Fig. 4. The quantity and percentage of deposited sediment in each sublayer a final filtration time for the dual-media filter of BOPS-sand and $V = 5.81$ m/h.
(a) Dual-media BOPS-sand ES = 0.6 – 0.5 mm.
(b) Dual-media BOPS-sand ES = 0.8 – 0.5 mm.
(c) Dual-media BOPS-sand ES = 1.0 – 0.5 mm.

ES = 1.0:0.5 mm decreases to 39% (or 0.052 v/v) and 47% (or 0.044 v/v) at filtration velocity of 5.81 and 3.62 m/h respectively.

A detail observation of the quantity of deposited sediment in the sand layer should be analysed as well. The percentage of deposited sediment in sand layer for the dual-media BOPS-sand with ES = 0.6:0.5 mm are 39% (or 0.021 v/v) and 26% (or 0.013 v/v) at filtration velocity of 5.81 and 3.62 m/h respectively. While the percentage of sediment deposited in sand layer for the dual-media BOPS-sand with ES = 1.0:0.5 mm increase to 61% (or 0.076 v/v) and 53% (or 0.05 v/v) at filtration velocity of 5.81 and 3.62 m/h respectively. Due to a high efficiency and removal percentage of suspended particles for the smaller size of sand (as indicated in Table 2), the majority of the deposited sediment were trapped in the first and second sublayer of sand media as shown in Figs. 4 and 5. Therefore, it can be concluded that a dual media filter of BOPS-sand with the BOPS upper layer is functioning as a large reservoir while the sand lower layer is functioning as a final filter and thus performs as high capacity filter that produces high quality filtrate.

A similar trend is shown by Fig. 5, except that the total capacity of sediment deposited in all dual-media filters for the lower velocity (3.61 m/h) is slightly less. Furthermore, the higher filtration velocity will bring the deposited sediment deeper into the lower sublayers. This

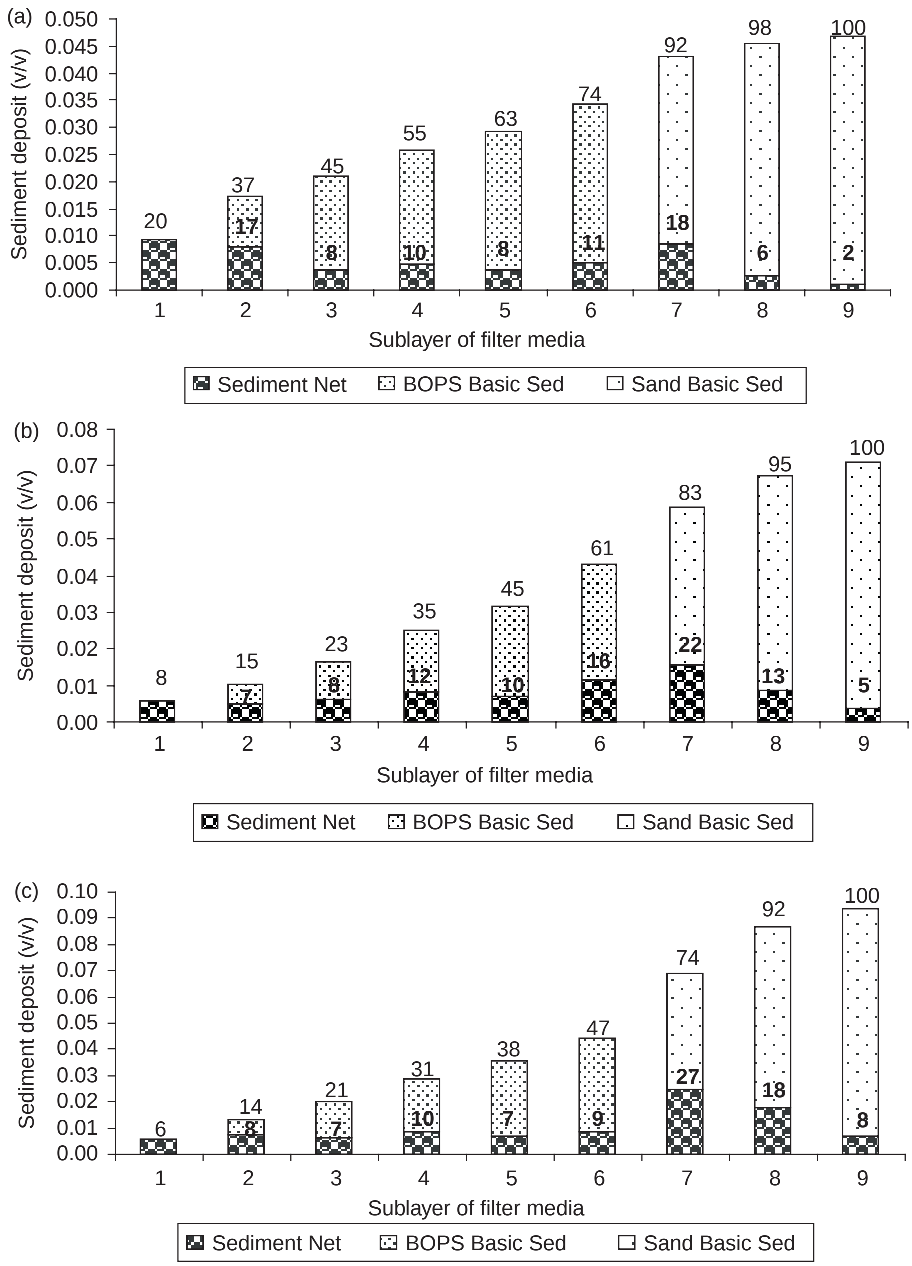


Fig. 5. The quantity and percentage of deposited sediment in each sublayer at final filtration time for the dual-media filter of BOPS-sand and $V = 3.62$ m/h.
(a) Dual-media BOPS-sand ES = 0.6 – 0.5 mm.
(b) Dual-media BOPS-sand ES = 0.8 – 0.5 mm.
(c) Dual-media BOPS-sand ES = 1.0 – 0.5 mm.

phenomenon is clearly indicated by the reduced percentage of deposited sediment in the BOPS layer at the higher filtration velocity of 5.81 m/h (as compared to 3.62 m/h) that occurred in all the dual-media filters tested.

## 4. Conclusion

This study focuses on a proposed a new matrix approach with incorporated RT model in determining the specific sediment deposit, at specified times and sublayers of filter media.This new matrix approach can succesfully predict the net and cumulative quantity as well as the percentage of the sediment deposited in each sublayer of filter media and at various time as filtration progresses. This method was shown to be accurate as the results fitted very well with the experimental data in terms of sediment deposited.

Furthermore, the added advantage of using this approach for determining the volume of sediment deposited in each sublayer at progressing filtration time is that the thickness and the percentage in respective media of BOPS and sand for the dual-media BOPS-sand filter can be determined. In addition, this analysis can determine the performance or effectiveness of a new filter media especially BOPS media. It was found that the dual-media BOPS-sand filter has a great potential to be used in treating raw water.

## Notation

- $As$ – porosity function, dimensionless
- $C$ – concentration of suspended solids, mg/L
- $C_e$ – effluent concentration of suspended solids, mg/L
- $C_o$ – influent concentration of suspended solids, mg/L
- $dc$ – average diameter of grain media, m
- $dp$ – average diameter of kaolin clay particles, m
- $\delta C$ – derivative of concentration
- $\delta t$ – derivative of time
- $\delta z$ – derivative of media thickness
- $\delta\sigma$ – derivative of specific deposit
- $Ha$ – Hamaker constant, $1 \times 10^{-20}$ J
- $k_B$ – Boltzmann constant, $1.381 \times 10^{-23}$ J/K
- $L$ – depth of filter, m
- $N_{LO}$ – London group, dimensionless
- $N_R$ – relative size group, dimensionless
- $P_{10}, P_{60}$ – Percentage of passes at 10 and 60%
- $Pe$ – Peclet number, dimensionless
- $V$ – Superficial filtration velocity, m/h
- $t$ – time, h
- $\alpha$ – Attachment coefficient, dimensionless
- $\varepsilon, \varepsilon_o$ – porosity and initial porosity of media, dimensionless
- $_D$ – porosity of sediment, dimensionless
- $\gamma$ – porosity function, dimensionless
- $\eta_{total}$ – total transport efficiency, dimensionless
- $\eta_D$ – transport efficiency due to diffusion, dimensionless
- $\eta_I$ – transport efficiency due to interception, dimensionless
- $\eta_S$ – transport efficiency due to gravity, dimensionless
- $\lambda$ – filter coefficient
- $\mu$ – dynamic viscosity of water, N.s/m$^2$
- $\rho_S$ – density of suspended particles, kg/m$^3$
- $\rho_W$ – density of water, kg/m$^3$
- $\sigma$ – specific deposit in v/v
- $\Delta t$ – time interval, h
- $\Delta L$ – thickness of sublayer, m

## Appendix

$$A_S = \frac{2(1-\gamma^5)}{2-3\gamma+3\gamma^5-2\gamma^6} \tag{10}$$

$$\gamma = (1-\varepsilon)^{1/3} \tag{11}$$

$$N_{LO} = \frac{4\,Ha}{9\pi\, d_P^{\,2} V} \tag{12}$$

$$N_R = \frac{d_P}{dc} \tag{13}$$

where, $\eta_S$ and $Pe$ are as in Eqs. (14) and (15):

$$\eta_s = \frac{g(\rho_P - \rho_W)\, d_P^{\,2}}{18\,\mu_w V} \tag{14}$$

$$Pe = \frac{3\pi \mu_W\, d_P\, dc\, V}{k\,T} \tag{15}$$

Root Mean Square Error, RMSE:

$$RMSE = \left[\frac{\sum_{i=1}^{m}\left(X_i^p - X_i\right)^2}{n_r}\right]^{1/2} \tag{16}$$

## References

[1] J.E. Altoe, P. Bedrikovetsky, A.G. Siqueira, A.L.S. de Souza and F.S. Shecaira, Correction of basic equation for deep bed filtration with dispersion, J. Pet. Sci. Eng., 51 (2006) 68–84.

[2] American Public Health Association, Standard Methods For the Examination of Water and Wastewater, 19th Ed. American Public Health Association, Washington, DC, 1995, 1108.

[3] R. Bai and C. Tien, Particle deposition under unfavorable surface interactions, J. Colloid Interface Sci., 218 (1999) 488–499.

[4] H.B. Dharmappa, H. Prasanthi, M.U. Krishna and Y. Xiao, Estimation of empirical coefficients of a granular filtration model, Water Res., 31(5) (1997) 1083–1091.

[5] T. Iwasaki, Notes on sand filtration, Journal of American Water Works and Association, 29(10) (1937) 1591–1602.

[6] S. Kawamura, Integrated design of water treatment facilities, 2nd Edn, John Wiley and Sons, New York, USA, 2000.

[7] Y.S. Kim and A.J. Whittle, Filtration in a porous granular medium: Simulation of pore scale particle deposition and clogging, J. Transport in Porous Media, 65 (2006) 53–87.

[8] E. Lin, D. Page and P. Pavelic, A new method to evaluate poly-disperse kaolinite clay particle removal in roughing filtration using colloid filtration theory, Water Res., 42 (2008) 669–676.

[9] R.I. Mackie and R. Bai, Suspended particle size distribution and the performance of deep bed filters, Water Res., 26(12) (1992) 1571–1575.

[10] R.I. Mackie and Q. Zhao, A framework for modeling removal in the filtration of poly-disperse suspension, Water Res., 33(3) (1999) 794–806.

[11] J.M. Montgomery, Water treatment principles and design, John Wiley and Sons, New York, USA, 1985.

[12] C.S.P. Ojha and N.J.D. Graham, Theoretical Estimates of bulk specific deposit in deep bed filters, Water Res., 27(3) (1993) 377–387.

[13] S. Osmak, D. Gosak and A. Glasnivic, Dynamic mathematical model of deep bed filtration process, Computers Chem. Eng., 21 (1997) 763–768.

[14] S. Qi, Expression for critical suspended particle size in granular media filtration processes, Water Res., 32(9) (1998) 2856–2859.

[15] R. Rajagopalan and C. Tien, Trajectory analysis of deep-bed filtration with the sphere-in-cell porous media model, AIChe J., 22(3) (1976) 523–533.

[16] J.E. Tobiason and B. Vigneswaran, Evaluation of a modified model for deep bed filtration, Water Res., 28(2) (1994) 335–342.

[17] N. Tunfenkji and M. Elimelech, Correlation equation for predicting single-collector efficency in physicochemical filtration in saturated porous media, Environ. Sci. Technol., 38 (2004) 529–536.

[18] G.J. Williams, B. Sheikh, R.B. Holden, T.J. Kouretas and K.L. Nelson, The impact of increased loading rate on granular media, rapid depth filtration of wastewater, Water Res., 41 (2007) 4535–4545.

[19] K.M. Yao, M.T. Habibian and C.R. O'Melia, Water and wastewater filtration: concept and application, Environ. Sci. Technol., 5(11) (1971) 1105–1112.