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Impact of loading rate and filter height on the retention factor in the model of total coliform (TC) removal in direct rapid sand filtration

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ABSTRACT

As a promising technology for wastewater reuse, direct rapid sand filtration has been widely used throughout the world, especially in arid developing and emerging countries. Retention factor describing the equilibrium between retained and mobile total coliform (TC) bacteria plays an important role in the model of TC removal in direct rapid sand filtration. Little attention has been given to the relationship between retention factor and loading rate as well as filter height, two critical parameters impacting retention factor. Therefore, the influence of loading rate as well as filter height on retention factor was discussed. Results showed that retention factor decreased dramatically with loading rate ranging from 9 to 15 m/h, but increased slightly as loading rate ranged from 5 to 9 m/h, which is a little different with the variation of suspended solids and total phosphorus removal efficiency. Retention factor decreased significantly with filter height of 0–30 cm and 120–150 cm, but reduced uniformly with filter height of 30–120 cm. It was deduced that the optimum loading rate and filter height may be 9 m/h and 90–120 cm, respectively. Increasing flocculant could overcome retention factor reduction resulted from higher loading rate or smaller filter height.

Keywords: Direct rapid sand filters; Filter height; Flocculant dose; Loading rate; Retention factor; Total coliform (TC)

1. Introduction

With increasing water demand and dwindling water resources in many countries, wastewater reuse gains more and more importance as it reduces environmental damage and decreases the demand made on natural freshwater sources [1]. A continuously increasing world population as well as higher quality standards and expenses for drinking water also push the numerous efforts to apply wastewater/water reuse systems [2].

As a process in wastewater reclamation, direct rapid sand filtration is commonly employed to remove particles and pathogens [3–5]. Main advantages of direct rapid sand filtration systems are its simplicity and economical construction, operation, and maintenance using local materials and skills [6,7].

Although the process is widely used throughout the world, relatively little attention has been given so far to

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modeling the removal of total coliform (TC) from secondary effluent. This is principally due to the inherent difficulties of attempting to describe mathematically the complex physicochemical and biological mechanisms involved in the process [8,9]. The weak capacity of TC removal in direct rapid sand filtration may be another reason. Research showed TC bacteria removal of 0.6–1.5 log units depending on raw water quality, filter design, and loading rate [10]. Actually, the operation effect of direct rapid sand filtration has a significant impact on the disinfection efficiency [11,12].

Li et al. [10] ever indicated a model based on first-order kinetics to simulate TC removal from secondary effluent in direct rapid sand filtration, namely the elimination and inactivation of total fecal coliform both in the water phase and the sand bed was modeled following first-order kinetics. The model illustrated measured concentrations of TC bacteria compared to simulation results in direct rapid sand filters as a function of filter length at loading rates of 5, 7, and 10 m/h. In this model, the parameter of retention factor describing the equilibrium between retained and mobile TC bacteria related to the specific sand surface area and as a function of filter bed depth (m^3/m^2) plays an important role [10]. The retention factor is related to various parameters of direct rapid sand filter as the removal mechanisms such as transport, straining, and adsorption leading to retention are summarized as the parameter. As one of the most important design parameters for direct rapid sand filtration, loading rate is closely related to the production capacity of a filter, the required filter surface area [6]. Although the relation between loading rate and retention factor is of great importance when applying the model, the impact of the loading rate on retention factor is still unclear.

Therefore, the goal of this research was focused on two previously unaddressed issues, the first of which entails characterizing the effect of loading rate on the retention factor in the model of tertiary direct rapid sand filtration at a pilot plant under conditions that mimicked a full-scale treatment plant. Taking into account that the retention factor varies with filter height, the relation between them was also considered. The second aim of this research was to determine whether increasing the flocculant dose could overcome the negative impact of higher loading rate or smaller filter height on retention factor. Removal efficiency of suspended solids (SS) and total phosphorus (TP) was also studied with the exception of retention factor for TC. The impossibility of determining optimum loading rate and filter height combining variation of retention factor and SS as well as TP removal efficiency was also discussed.

2. Materials and methods

2.1. Raw secondary effluent quality

This study was conducted from May 2011 to January 2012 at one of wastewater treatment plants in Taihu Lake river basin (in southern Jiangsu, China), which typically treats 100,000 m^3/d of municipal wastewater by anaerobic–aerobic–oxidation process. Combination of direct rapid sand filtration and UV disinfection was applied as the tertiary treatment technology in the wastewater treatment plant. During the study period, average raw wastewater quality was characterized by a biological oxygen demand (BOD) of 165 mg/L, SS of 83 mg/L, and TP of around 2.6–4.7. Secondary effluents had BOD levels of 8 ± 2 mg/L, SS of 15–20 mg/L, and TP of 0.37–0.56 mg/L.

2.2. Pilot plant design

Secondary effluent from the full-scale clarifier effluent well was pumped to the pilot plant (Fig. 1). Polyaluminum chloride as flocculant at optimum dose was added using an additional peristaltic pump, and

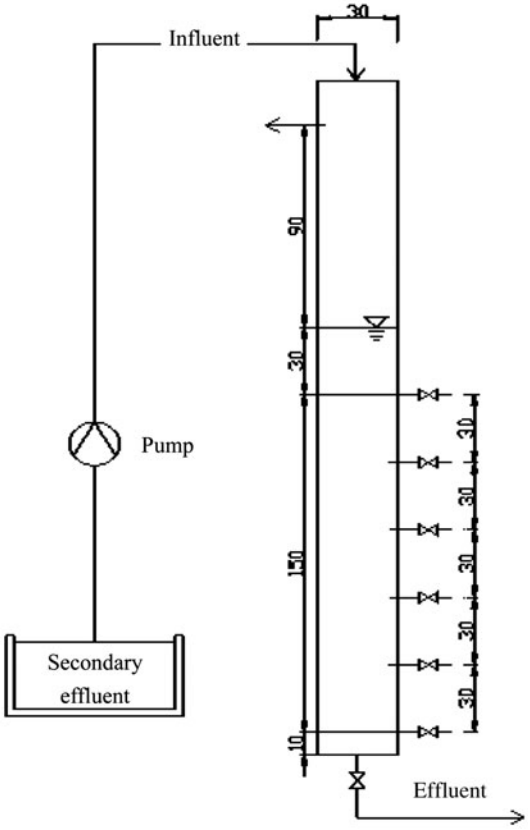


Fig. 1. Schematic of the filter column experimental setup.

mixed through static mixers. Coagulated flow entered the sand filter at the typical pilot system flow rate of 5 m^3/h. This flocculated effluent was gravity fed to the filter columns. After each filter run, the column was backwashed for 2 min with air at 15 L/(m^2 s) and for 5 min with filtered water at 6 L/(m^2s). Water levels above the top of filter media were recorded and allowed to rise up to 110 cm before entering into the next filter cycle.

The pilot filter consisted of one column that operated at different loading rate. The filter column contained a quartz sand bed of 150 cm of 1.5 mm diameter supported by 5 cm of gravel of 2–4 mm diameter on top of 5 cm of gravel of 4–8 mm diameter (Fig. 1). The column was constructed from a transparent, 30-cm inner diameter PVC pipe and had a total height of 3 m. Six sampling ports were arranged on the column. An outflow weir controlled the minimum supernatant water level of 30 cm. Filter media characteristics and operating conditions are listed in Table 1.

2.3. Flow setting and sample collection

Filtration was performed at constant approach loading rates of 5, 7, 9, 11, 13, and 15 m/h. The loading rate was controlled using flow meters mounted at the inlet of column. To insure constant flow velocity, the set flow rate was monitored twice per filter cycle.

After setting the loading rate, influent and effluent water samples from sampling ports placed at 0, 30, 60, 90, and 120 cm below the sand bed surface were taken. The samples were collected in 250-mL sterile glass bottles. The sand samples retained on filter media in the filter horizons of 0, 30, 60, 90, 120, and 150 cm depth at different loading rates were also taken to calculate the value of retention factor.

2.4. Sample analysis and retention factor calculation

TC samples were analyzed using membrane filtration (MF) technique [13] within a maximum of 3 h after samples collection; analysis was conducted at the laboratory of the wastewater treatment plant in Jiangsu province. Samples were taken at different loading rate as well as different bed depth and analyzed in triplicates. Dilution of 100 times was used for water samples. One hundred milliliters of diluted water samples were filtered through pre-sterilized, gridded 0.45 μm membrane. Magenta sodium sulfite medium was used to culture TC. The method of determining TC on sand surface was described elsewhere [14]. Analysis methods of SS and TP in influent and effluent samples were gravimetric method and spectrophotometric method.

Table 1
Overview of the values of filter material characteristics

Parameters	Explanation	Column
d_{10} (mm)	Effective size of grain	1.5 mm
ρ_b (kg/m^3)	Density of grain	2,650
p (%)	Porosity	40
U	Uniformity coefficient	1.2

The values of retention factor were determined from TC concentrations in the water and those retained on sand in different filter depths. Calculation of retention factor was expressed as Eq. (1).

$$\text{Retention factor} = [\text{retained TC}]/[\text{mobile TC}]/[\text{specific sand surface area}] \quad (1)$$

In Eq. (1), retained TC represents the amount of TC retained on the surface area at certain filter depth. Mobile TC means the concentration of TC in the water at the same filter depth. Specific sand surface area (A_s) was approximated by Eq. (2).

$$A_s = \frac{6,000}{d_{10} \cdot (1 + 2\log U)} \cdot (1 - p) \quad (2)$$

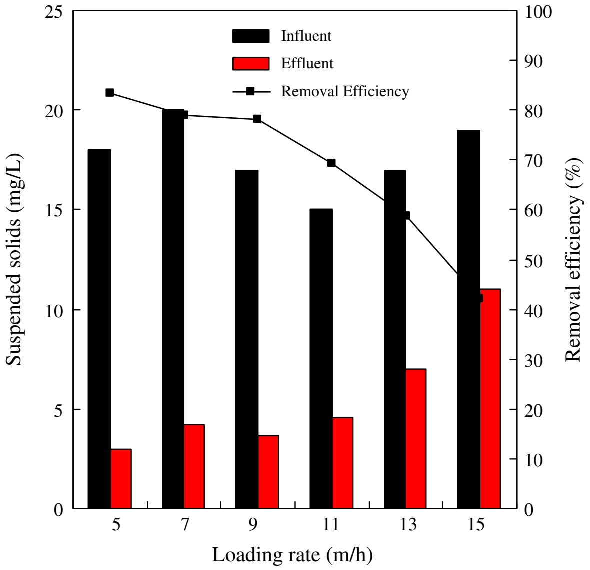
with p being porosity [15].

3. Results and discussion

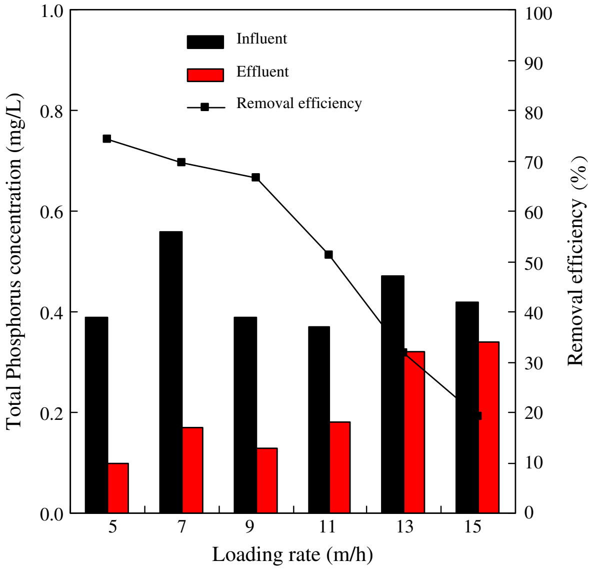
3.1. Removal of SS and TP

As SS and TP are two important parameters to evaluate the operation efficiency of wastewater treatment system, the removal of the two pollutants is considered in the research.

Fig. 2 illustrates the influent and effluent concentration as well as the removal efficiency of SS and TP in the direct rapid sand filter at different loading rates. As evident from the data in Fig. 2, the direct rapid sand filter of low loading rate removed more SS or TP than that of high loading rate. From Fig. 2, it was found that the mean removal efficiency of SS and TP was around 74.4 and 83.3% for the loading rate 5 m/h, respectively. Both SS and TP removal efficiencies were a little higher than that of 50–70% and 50–80% reported by Üstün [16]. This is because that they adopted higher loading rate in their study and different influent qualities. For higher loading rates, SS and TP removal efficiencies both consistently decreased (Fig. 2). The mean filter effluent SS and TP increased from 0.1 to 0.34 mg/L and from 3 to 11 mg/L,



(a) Suspended solids



(b) Total phosphorus

Fig. 2. Illustration showing secondary effluent, filter effluents, and removal efficiency of SS and TP for different loading rates.

respectively, as the loading rate increased over the loading rate range of 5 to 15 m/h (Fig. 2). The variation of removal efficiency for SS or TP was similar as the loading rate increased from 5 to 15 m/h. The reason for this phenomenon is that the removal mechanism of the two pollutants is similar. Both of them are removed through the flocculation process.

Fig. 2 also shows that as loading rate increased from 5 to 9 m/h, the removal efficiency of those two pollutants decreased slightly. This might be attributed to more pollutants load passing through the filter bed. But those two removal efficiencies reduced significantly as loading rate ranging from 9 to 15 m/h. The reason for this phenomenon was related to the decrease of hydraulic retention time and flocculation time in filter columns. Scouring of high velocity water on filter media was another factor leading to the deterioration of effluent quality [7]. It could be further concluded that optimum loading rate for SS and TP removal may be around 9 m/h.

3.2. *Influence of temperature and pH on the values of retention factor*

In this research, temperature ranged from 17.8℃ recorded at the effluent to 24.6℃ recorded at the influent. The temperature of the influent (average 23.0 ± 1.6℃) was observed to be higher than effluent temperature (average 18 ± 1.2℃).

In direct rapid sand filtration, temperature-related processes influencing TC removal were flocculation and bacterial decay [10]. Although temperature had a strong impact on the rate of chemical and biological reactions [17], Kadlec and Reddy [18] ever pointed that suitable temperature ranged from 15 to 35℃ for biological reactions. And flocculation of polyaluminum chloride also had a wide temperature range around [19]. The temperatures measured in direct rapid sand filters in this study were generally within a suitable range for microbial activities and chemical reactions and the variations observed are considered insignificant (maximum range was 3.0℃). Within this range of temperature variations, the influence of temperature on values of retention factor could be considered minor.

Tchobanoglous et al. [17] ever asserted that the pH range of 6–9 is suitable for high microbial activities. And suitable pH of polyaluminum chloride ranges from 5.0 to 9.0 [19]. In these experiments, the water pH ranged from 6.2 to 7.5. Therefore, flocculation and microbial processes were considered to be at optimum conditions during the study. The change of pH was negligible and did not influence values of retention factor.

3.3. *Influence of loading rate and filter height on values of retention factor*

One goal of this work was to determine the influence of loading rate and filter height on the retention factor. According to the values of TC concentrations in the water and those retained on sand in different filter depths as well as specific sand surface area, the values of retention factor were calculated [14]. Retention factor values at different loading rate and filter height are listed in Tables 2 and 3, respectively.

From Table 2, it was observed that retention factor for TC removal varied with loading rate and filter height. As the loading rate ranged from 5 to 9 m/h, the value of retention factor increased from 0.242 to 0.273 for the top sand layer. The trend for other sand layer was similar to the top sand layer. This is because for higher loading rates as loading rate ranging from 5 to 9 m/h, increased particle load on sand surface results in higher particle deposition [20]. Higher particle deposition means more TC will be retained on sand surface. Therefore, the retention factor value will increase. However, the retention factor at top layer decreased from 0.273 to 0.163 as loading rate increased from 9 to 15 m/h. Other sand layer presented the same trend of retention factor values. The reason for this phenomenon is that increase of loading rate reduced the contact time between flocs formed in flocculation process and sand surface. Correspondingly, the flocculation time decreased [21].

The opposite pattern of retention factor variation may be explained as follows. As loading rate ranging between 5 and 9 m/h, the influence of particle load is larger than that of contact time. As loading rate ranging from 9 to 15 m/h, contact time has a larger impact on TC removal compared with particle load. Overall, higher loading rate enhanced the transport of bacteria through the deep filter, while reduced the attachment efficiency because of much lower retention time and larger hydrodynamic forces on filter media surface [22], and loading rate around 9 m/h was right at the critical line. The maximum of retention factor at loading rate of 9 m/h might indicate the optimum loading rate for this direct rapid sand filter, which was the same with that obtained from the SS and TP removal.

According to Table 2, it was also observed that the retention factor varied with filter height. The value of retention factor decreased significantly as filter height extending from 0 to 30 cm for all loading rates tested. It indicated that the majority of TC removal occurred in the top few inches of sand bed due to multiple particles and organisms clumping together to form one aggregate enhancing the removal of TC [23], consistent with the current understanding of particle removal mechanisms, namely transport and attachment [24]. In direct rapid sand filter, cake formation at top of the filter also contributed to the larger retention factor value in the top layer [7]. As filter bed height ranged from 30 cm to 120 cm, the value of retention factor decreased uniformly. However, retention factor value decreased significantly as filter height increased from 120 to 150 cm because concentration of TC in water phase reduced gradually as water passed through the filter bed [10]. This coincided with TC removal in direct rapid sand filter.

Table 2
Determination of the retention factors in the sand bed of direct rapid sand filters 5–9 m/h

Phase	Bed depth (cm)	Retained TC (CFU/100 mL)	TC in mobile phase (CFU/100 mL)	Retained TC per mobile TC	Specific sand surface area	Retained TC per mobile TC and sand surface area
5 m/h	0	1.16E+08	2.31E+05	501	2072	0.242
	30	3.09E+07	1.23E+05	251		0.121
	60	2.24E+07	9.24E+04	242		0.117
	90	1.70E+07	7.95E+04	213		0.103
	120	7.85E+06	4.57E+04	172		0.083
	150	7.01E+05	2.60E+04	27		0.013
7 m/h	0	1.49E+08	2.71E+05	549		0.265
	30	5.33E+07	1.95E+05	274		0.132
	60	4.09E+07	1.54E+05	265		0.128
	90	2.72E+07	1.23E+05	222		0.107
	120	1.43E+07	7.56E+04	189		0.091
	150	2.53E+06	5.55E+04	46		0.022
9 m/h	0	1.43E+08	2.53E+05	566		0.273
	30	5.82E+07	1.94E+05	300		0.145
	60	3.29E+07	1.17E+05	282		0.136
	90	2.20E+07	9.06E+04	242		0.117
	120	1.49E+07	6.53E+04	228		0.11
	150	3.62E+06	5.46E+04	66		0.032

Table 3
Determination of the retention factors in the sand bed of direct rapid sand filters 11–13 m/h

Phase	Bed depth (cm)	Retained TC (CFU/100 mL)	TC in mobile phase (CFU/100 mL)	Retained TC per mobile TC	Specific sand surface area	Retained TC per mobile TC and sand surface area
11 m/h	0	8.97E+07	2.01E+05	445	2072	0.215
	30	4.08E+07	1.60E+05	255		0.123
	60	2.34E+07	1.04E+05	226		0.109
	90	1.88E+07	8.82E+04	213		0.103
	120	1.24E+07	6.97E+04	178		0.086
	150	3.62E+06	6.24E+04	58		0.028
13 m/h	0	7.24E+07	1.92E+05	377		0.182
	30	3.88E+07	1.67E+05	232		0.112
	60	2.48E+07	1.27E+05	195		0.094
	90	1.50E+07	1.13E+05	133		0.064
	120	6.27E+06	9.17E+04	68		0.033
	150	2.52E+06	8.68E+04	29		0.014
15 m/h	0	6.48E+07	1.92E+05	338		0.163
	30	3.79E+07	1.79E+05	211		0.102
	60	2.18E+07	1.46E+05	149		0.072
	90	1.42E+07	1.40E+05	102		0.049
	120	7.09E+06	1.27E+05	56		0.027
	150	2.82E+06	1.24E+05	23		0.011

3.4. Increasing flocculant dose to overcome the impacts of higher loading rate or smaller filter height on retention factor

Combining the data of Tables 2 and 3, it was found that the retention factor decreased significantly as loading rate increased from 9 to 15 m/h. As a symbol of TC removal, the decrease of retention factor means that the removal efficiency of TC declined. Therefore, another aim of this research was to determine whether increasing the flocculant dose could overcome the negative impact of higher loading rate or smaller filter height on retention factor. Loading rate of 15 m/h was investigated, and the flocculant dose was increased from 10 to 20 mg/L. The results were listed in the last row of Table 4.

According to Table 4, it was noted that retention factor for flocculant dose of 20 mg/L increased much compared with that for flocculant dose of 10 mg/L. At the top sand layer, retention factor value increased from 0.163 to 0.243, and the same trend of retention factor variation at other sand layer was also observed. This may be attributed to the rise of reaction rate coefficient illustrating TC elimination/inactivation (by flocculation, die off, predation, lysis) [10]. This kind of results was also similar to Williams' results [6] about particle and bacteria removal in direct rapid sand filter.

Table 4
Value of the retention factor at different polyaluminum chloride dose at filter loading rate of 15 m/h

		Retained TC per mobile TC and sand surface area	
Filter loading rate	Bed depth (cm)	Polyaluminum chloride dose (10 mg/L)	Polyaluminum chloride dose (20 mg/L)
15 m/h	0	0.163	0.243
	30	0.102	0.128
	60	0.072	0.132
	90	0.049	0.11
	120	0.027	0.087
	150	0.011	0.023

4. Conclusions

The retention factor increased with loading rate ranging from 5 to 9 m/h, and decreased with loading rate ranging from 9 to 15 m/h. The retention factor always decreased with filter height. Retention factor decreased significantly as filter height ranging from 0 to 30 cm and 120 to 150 cm, and decreased uniformly as filter height ranging from 30 to 90 cm. SS and TP removal efficiency in direct rapid sand filter decreased slightly as loading rate ranging from 5 to 9 m/h, while reduced significantly as loading rate increased from 9 to 15 m/h. Combining the impact of loading rate on retention factor and SS as well as TP removal efficiency, it is further deduced that the optimum loading rate and filter height may be around 9 m/h and around 90–120 cm, respectively. And the impact of higher loading rate or smaller filter height on retention factor can be overcome by increasing flocculant dose.

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