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Flow patterns of multi-soil-layering systems

Yi-Dong Guan[a,b,c,*], De-Fu Xu[a,b], Xin Chen[d], An-Cheng Luo[c], Hua Fang[b], Yu-Zhi Song[b]

[a] *Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control, China*
Tel. +86 25 5873 1090; Fax: +86 25 5873 1090; email: yidongguan@163.com
[b] *School of Environmental Sciences and Engineering, Nanjing University of Information Science & Technology, Nanjing 210044, China*
[c] *College of Environmental and Resource Sciences, Zhejiang University, Hangzhou 300191, China*
[d] *Nanjing Institute of Environmental Science (Ministry of Environmental Protection), Nanjing 210042, China*

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ABSTRACT

Multi-soil-layering (MSL) systems permit higher hydraulic load rates (HLR) and pollutant loads than some conventional soil systems by forming the alternating structures inside to enhance the filtration ability of soil. However, the quantitative evaluations of water movement in MSL are insufficient to be understood. Residence time distribution (RTD) is a tool to characterize the mixing and flow within reactors and is useful for troubleshooting existing reactors. In this study, pulse tracer tests were conducted to determine the RTD to investigate the flow patterns of MSL. Results show that the back-mixing extent of MSLs was moderate dispersion under HLR 200, 400, 800, and 1,600 $\mathrm{L/(m^2\,d)}$, and the RTD of them indicate evident flow patterns of CSTR. Residence time shows a significantly negative correlation with the dead zone ($p = 0.001$). The dead zone ratio of the MSLs were 41.0%, 52.3%, 59.6%, and 38.8% under HLR 200, 400, 800, and 1,600 $\mathrm{L/(m^2\,d)}$, respectively.

Keywords: Multi-soil-layering system; Flow patterns; Dead space; Tracers; Residence time distribution

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1. Introduction

Natural processes, such as land application and constructed wetlands, offer the advantages of easy construction and low maintenance costs [1], and are widely used all over the world. The multi-soil-layering (MSL) system has been applied in wastewater treatment as a decentralized land application process, and MSL enhances the soil's infiltration ability through the inside structure, an alternating brick layer-like pattern of soil-mixed block (SMB) and permeable layer (PL) [2–4]. Then, MSL can sustain higher hydraulic load rate (HLR) and pollutant load than some conventional soil systems because of the larger pore volume of the media packed through the internal structure [2,4]. However, non-ideal flow may occur in MSL at varying extents, for instance, channeling and short-circuiting, due to the different permeabilities of the PL and SMB which has been pointed out by Luanmanee et al. [3]. Furthermore, MSL's manner of operation, namely non-saturated seepage, may further intensify the short-cut flow [5].

Residence time distribution (RTD) can help to predict the velocity distribution of fluid in a reactor [6], and is a useful tool for measuring hydraulic

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*Corresponding author.

performance (short circuit and dead zones) of reactors under different operating conditions [6,7]. RTD also has an advantage over empirical designs and operating criteria for natural processes, in that empirical designs provide insufficient insight into performance optimization and the mechanism of fluid flow under variable wastewater loads [8]. Tracer experiments are a convenient measure with which to evaluate RTD. To date, there have been few reports on the flow patterns of MSL.

Given that, clear estimation of the practical flow inside MSL is not currently available; this research aims to analyze the flow patterns and behavior of MSL and quantify its dead volume.

2. Material and methods

2.1. Experimental set-up

The experimental reactors used were described in detail in our last report [2], and the details are summarized as follows. Four 37.5 L tanks (effective volume of 26 L), 50 cm long × 10 cm wide × 75 cm deep, were each filled with approximately 16.6 kg of zeolite (particle size of 3 mm to 5 mm) composed of 24 SMBs (each weighing 192.9 g). PL and SMBs were alternately surrounded in a brick-like pattern. The HLR of the four reactors were 200, 400, 800, and 1,600 $L/(m^2 d)$, and the corresponding nominal hydraulic retention times (HRT) were 31.7, 13.0, 6.6, and 3.5 h, respectively. The four MSLs were labeled M200, M400, M800, and M1,600.

2.2. Tracer tests

The tracer tests were performed after the four MSLs have been operated for more than 184 days for landfill treatment [2]. Then, four MSLs were leached by tap water for four weeks and then flushed with water until the electroconductivity of the effluent outlet was approximate to the influent water (about 150–200 μs/cm). Potassium chloride (KCl) was used as a tracer to determine the RTD curves of four MSLs.

The recovering ratios of KCl were 11.4%, 76.0%, 81.0%, and 47.2% under HLR 200, 400, 800, and 1,600 $L/(m^2 d)$, respectively. According to RTD experiment results in two soil filters [9], the tracer recovery ratios (bromide) are 92 and 56% under 30 and 16 mm/d HLR, respectively. In a vertical subsurface flow CWs [10], the recovery proportion of tracer, rhodamine WT, was about 58–67%. Therefore, the tracer recovery ratio in this experiment was considered to be acceptable. It is worth noting that the lower tracer recovery of M200 might be from two factors: a higher part of tracer mass not counted owing to the longer tail and a higher portion of tracer absorbed under the low flow rate.

A 12% KCl solution (in mass concentration, 20 mL) was injected as a pulse into the MSL inlet, and then the electroconductivity of the effluent outlet was detected using a conductivity instrument (Lida DDS—11AW, China). Each tracer test lasted for more than three times the nominal HRT. KCl concentrations were calculated by establishing the functional relationship between electroconductivity and KCl concentration, which is according to the Refs. [11,12]. The method is listed as follows in details. A calibration line for the salt concentration and the electrical conductivity was determined using water by adding a known amount of salt to the wastewater and measuring the increase in electrical conductivity. Linear fitting was used to find the calibration line from the concentration-electrical conductivity data. Before the curve fitting, the initial electrical conductivity was subtracted in each measuring points. The calibration line was used to calculate the concentration of tracer from electrical conductivity data.

Steady state conditions were maintained during the tracer tests. The fluent velocity of M200, M400, M800, and M1,600 was obtained by setting the flow to 6.27, 13.23, 27.71, and 52.37 mL/min, respectively, by a peristaltic pump (Longer BT100–1 J, China), and the corresponding error rates of flow rates were 3.8, 3.3, 0.1, and 4.0%.

2.3. Data analysis

$E(t)$, mean residence time $\bar{t}$ and variance of RTD σ_β^2 can be expressed as Eq. (1):

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt}, \quad \bar{t} = \frac{\int_0^\infty tE(t)dt}{\int_0^\infty E(t)dt}, \quad \sigma_\beta^2 = \int_0^\infty t^2E(t)dt - (\bar{t})^2 \tag{1}$$

where t is time (s), and the concentration-time curve of the tracer leaving the reactor is recorded as $C(t)$, mg/L. $E(t)$ is called the exit age distribution function (s^{-1}). β represents normalized residence time (dimensionless time units), $\beta = t/\bar{t}$; $\bar{t} = V/v$, mean residence time of fluid in a flow reactor; V, reactor volume (m^3); v, volumetric flow rate (m^3/s). The symbols and constants used in the numerical equations are defined in Supplementary material 1.

Both the axial dispersion model and the tanks-in-series model can be used to describe the flow patterns in a reactor. The dispersion model is applied for the relatively low back-mixing condition, with the dispersion coefficient D (m^2/s) representing the spreading process. By applying Fick's law and dimensional analysis, the axial dispersion model can be expressed as Eq. (2) [6]:

$$\frac{\partial C}{\partial \beta} = \left(\frac{D}{uL}\right)\frac{\partial^2 C}{\partial z^2} - \frac{\partial C}{\partial z} \tag{2}$$

where dimensionless D/uL indicates the spread in the whole vessel. When $\frac{D}{uL} \to 0$, the dispersion is negligible (plug flow); if $\frac{D}{uL} \to \infty$, the dispersion is large (mixed flow).

The tanks-in-series model is utilized for relatively large back-mixing, and the tracer concentration in time t is given by Eq. (3) [13]:

$$C(t) = \frac{C_0}{(N-1)!}\left(\frac{t}{HRT}\right)^{N-1} e^{-\frac{t}{HRT}},\ \sigma_\beta^2 = \int_0^\infty \frac{N^N \beta^{N+1} e^{-N\beta}}{(N-1)!}\, d\beta - 1 \tag{3}$$

where C_0 is the initial tracer concentration in the first tanks, and N is the series number.

RTD could also be used to estimate the dead space in the reactor and, hence, obtain information on mixing and hydrodynamics in the reactor. Researchers [12,14,15] have evaluated the dead space of constructed wetlands using RTD when determining the treatment level of a constructed wetland. Similarly, the dead space in MSLs is calculated to display their performance. The dead space of the reactor (V_d) can be calculated as by Eq. (4) [16]:

$$V_d = (1 - \bar{t}/HRT) \times 100\% \tag{4}$$

2.4. Data processing

Nonlinear curve fitting was analyzed and plotted using Origin 8.0 software.

3. Results

3.1. RTD studies

The tracer concentration response curves are shown in Fig. 1, and a summary of tracer response characteristics and hydraulic parameters are presented in Table 1. As shown in Fig. 1, the RTD of M200, M400, M800, and M1,600, all show evident characteristics of continuous stirred tank reactor (CSTR), i.e. a steep peak on the left lateral of RTD curve and a gradually declined curve which could be fitted with exponential decay equation [6]. The dimensionless dispersion number D/uL ranges from 0.16 to 0.08 with the increase of HLR. According to the researchers' conclusion [13], D/uL value is classified as the moderate dispersion for M200, M400, M800, and M1,600.

Table 1 indicates that the average residence time of M200, M400, M800, and M1,600 was 18.7, 6.2, 2.7, and 2.1 h, respectively, and the corresponding dimensionless times were 0.59, 0.48, 0.40, and 0.61

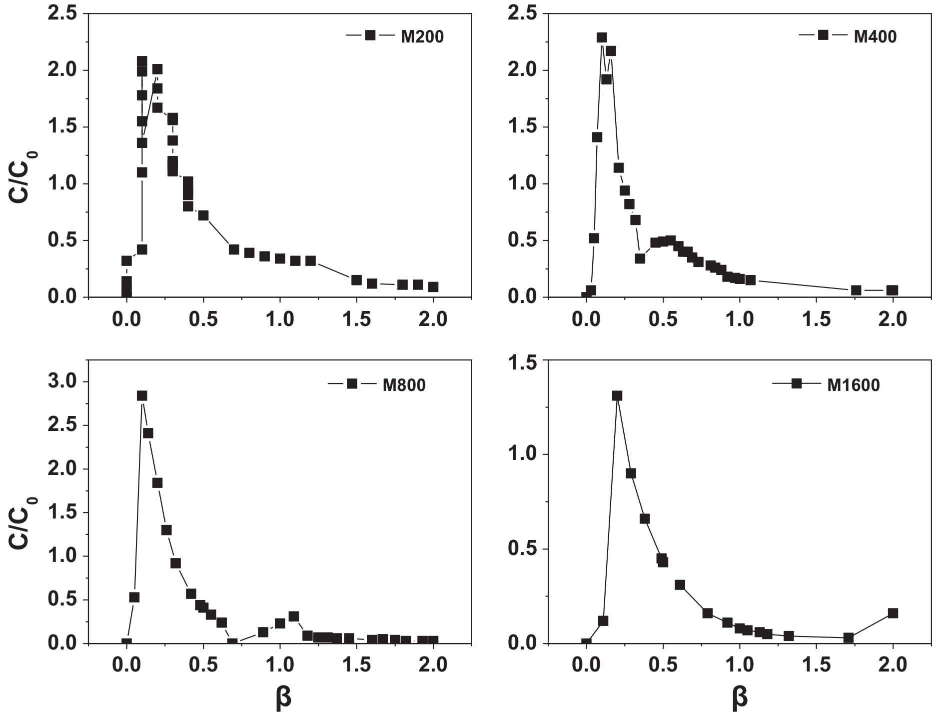

Fig. 1. RTD of MSLs under pulse addition.

Table 1
Experimental parameters of tracer flow pattern of MSLs

	M200	M400	M800	M1,600
HLR, L/(m^{2}d)	200	400	800	1,600
Nominal HRT, h	31.7	13.0	6.6	3.5
$\bar{t}$, h	18.7	6.2	2.7	2.1
Β	0.59	0.48	0.40	0.61
β^*	0.13	0.55	0.10	0.20
σ^2_β	0.25	0.22	0.17	0.31
D/uL	0.13	0.11	0.08	0.16
V_d, %	41.0	52.3	59.6	38.8

Note: β—normalized residence time, $\beta = t/\bar{t}$; β*—the dimensionless peak time of reactor, $\beta^* = \frac{\bar{t}_{\max}}{\mathrm{HRT}}$; σ^2_β—dimensionless variance of C curve, $\sigma^2_\beta = \frac{\sigma^2_{\mathrm{C}}}{\mathrm{HRT}^2}$, σ^2_{C}—variance of C curve, h^2.

respectively. Three critical time points were chosen to reflect the influence of reactor flow patterns on residence time, and it is listed in Table 2. The results reveal that 24.6%, 64.5%, 74.0%, and 64.1% liquid left MSLs in 1/2 HRT anT and 53.4%, 88.3%, 86.7%, and 88.1% liquid left the reactor in 1 HRT. The above data indicates that RTD curve was a positive skewed distribution and the corresponding peak points of the four MSLs were 0.13, 0.55, 0.10, and 0.20, respectively.

3.2. Estimation of dead space in MSL

Dead space in four MSLs is presented in Table 1. V_d vary from a high of 59.6% for M800 to a low of 38.8% for M1,600. To estimate the effect of residence time on dead space of MSL, linear regression of four MSLs were calculated and listed as Eq. (5) to set up the relationship between β and V_d. The linear fitting results show that V_d was significantly correlated with β at p value 0.001 (Eq. (5)), indicating that the dead zone volume ratio of MSLs was one of the critical factors affecting the residence time. The equation shows that longer residence time reduces the dead space and increases the volumetric efficiency of the reactors.

$$V_d = -99.379\beta + 99.602 \quad (R^2 = 0.999, p<0.001) \tag{5}$$

Table 2
Volume ratio of MSLs under different operating time

Time	M200	M400	M800	M1,600
1/2 HRT	24.6	64.5	74.0	64.1
1 HRT	53.4	88.3	86.7	88.1
2 HRT	100.0	100.0	100.0	100.0

4. Discussion

HLR is one of the main factors affecting the residence time of reactors. According to SATO's water movement report [17], the flow rate of SML (i.e. SMB) and PL increase linearly and exponentially, respectively as the increasing HLR. Therefore, there should be a critical region that only beyond the hydraulic region (i.e. HLR values), the water that could not flow into the SMB prefers to drain into the PL between SML as flow rate increases. It means the infiltration capacity increases in depth as liquid flow rate rises and D/uL decreases (less dispersion of fluid and more enhanced infiltration in the gravity direction). Moreover, the dead volume of MSL is directly related with the residence time, which has been illustrated in Section 3.2.

All RTDs in this test show characteristic quick peak and long tailing responses, indicating short circuiting and dead zones. The spike curve of RTD is greatly influenced by the inflow pattern of MSL, unsaturated seepage, which would favor the generation of short-cut flow [5] and may lower the actual residence time of the reactors. To alleviate the negative factor, the even distribution of influent is an effective measure [2,5]. In this experiment, the medium-speed filter paper is covered on the top surface of the MSLs to evenly distribute the influent to improve the water distribution. Then, the volume efficiency of MSL should be better than the one inflow point, since a larger portion of media volume came in contact with the inlet flow. On the other hand, the intermediate degrees of mixing in MSL would prolong the residence time. Since the granular of SMB (less than 1 mm) is much finer than that of PL (3–5 mm), the retardation capacity of SMB medium on the influent is stronger and then the permeability of the SMB was much lower than that of the PL (zeolite layer). This is in agreement with the report [5] and our field experience. Consequently, a part of water parcels was retarded in SMB and then it was released slowly. The slow movement of water parcels is depicted as the long tail of RTD (shown in Fig. 1) and is considered to be closely associated with stagnant dead zones [7]. This process could increase the retention time of liquid. It is noted that the retardation effect of inner medium on hydrodynamics and back-mixing degree in MSL is not clearly quantified and further research is needed to evaluate the flow behavior.

5. Conclusions

(1) Tracer experiment results show that the back-mixing extent of MSLs was moderate dispersion under HLRs of 200, 400, 800, and 1,600 L/(m^{2}d), and

the RTD of them indicate evident flow patterns of CSTR, (2) dead zones of MSLs were an important factor in determining the residence time and there was a significantly negative correlation ($p = 0.001$) between them. The dead zone ratios of the MSLs were 41.0%, 52.3%, 59.6%, and 38.8% under HLR 200, 400, 800, and 1,600 $\mathrm{L/(m^2\,d)}$, respectively.

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