Effect of Operating Parameters in a Submerged Membrane Adsorption Hybrid System: Mathematical Modeling and Experiments

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Abstract

This study aims at developing a simple and practical mathematical model to predict the performance of a submerged membrane adsorption hybrid system (SMAHS). Adsorption equilibrium and kinetic studies were first carried out with powdered activated carbon (PAC) for removing persisting organics from a synthetic wastewater. A series of short-term SMAHS experiments were conducted with preadsorption at different operating conditions such as aeration rate, backwash frequency, PAC dose and filtration flux. The Talu adsorption equilibrium and homogeneous surface diffusion model (HSDM) described well the isothermal adsorption behavior and adsorption kinetics respectively. The semi-empirical mathematical model formulated for membrane-adsorption system predicts successfully the performance of SMAHS in terms of Total organic carbon (TOC) removal. A coefficient known as “membrane correlation coefficient (MCC)” introduced in the model was found to be very useful in describing both the adsorption

of organics adsorbed onto the PAC and onto the membrane surface, and separation of PAC (with organics adsorbed on it) by the membrane.

Keywords: submerged membrane, fouling, water treatment, powdered activated carbon, critical flux

1. Introduction

The low-pressure driven membrane techniques such as microfiltration (MF) and ultrafiltration (UF) have been considered as indispensable treatment methods in the water and wastewater treatment applications to remove specific pollutants which are not normally removed by the conventional processes. MF and UF are excellent in removing microparticles, microorganisms, macromolecules, colloids and most bacteria. However, they can only partially remove color and dissolved organic matter (including natural organic matter (NOM) and synthetic organic compounds (SOCs)). Although the nanofiltration (NF) and reverse osmosis (RO) enable to remove the dissolved organic matter, they require higher pressure for their applications, hence higher operational cost. The membrane hybrid systems such as membrane-adsorption filtration systems are regarded as an alternative way to achieve a high removal efficiency of NOM and SOCs in a cost-effective manner [1].

The cross-flow microfiltration-adsorption (external loop) hybrid system demands higher energy for the operation. On the other hand, the submerged membrane adsorption hybrid system (SMAHS) requires only a low suction pressure, thus requiring lower energy for its operation. In SMAHS, the entire treatment activity (such as adsorption/biodegradation, liquid-solid separation, and sludge accumulation and withdrawal) can be carried out in a single unit. In this system, dissolved organic compounds which normally can pass through the MF are pre-adsorbed onto PAC particles. The PAC together with adsorbed organics is then separated by the membrane filtration process. The previous researches showed that the addition of PAC could: (i) provide better physical removal of NOM and SOCs, (ii) reduce the direct loading of dissolved organic pollutants onto the membrane, and (iii) prevent membrane fouling [2,3,4]. Seo *et al*. [5] conducted an experimental study on the biological activated carbon-microfiltration system for removing refractory organic matter (or persistent organic pollutants). The results showed that the system could remove 83% of total organic carbon (TOC) with 20 g/L PAC dose for 64 days. Furthermore, Kim *et al*. [4] found that the system could consistently remove more than 95% TOC with a PAC dose of 40 g/L for 40 days from a synthetic wastewater. It should be noted that this 40 g/L PAC is only added at the start of the experiment and the system has been running without any further addition of PAC. Nevertheless, they indicated that a high concentration of PAC could result in the formation of a cake at the membrane surface, thus reducing the effectiveness of physical cleaning by aeration and increasing the filtration resistance. Moreover, the drawback of PAC-membrane system is the initial fouling due to rapid, irreversible adsorption of organic substances onto the membrane surface [6]. Consequently, preadsorption of organics prior to the wastewater passing through the membrane could avoid the initial membrane fouling.

The performance of the membrane-adsorption hybrid system depends on reactor configuration, operating modes, carbon dose, carbon adsorptive characteristics and influent characteristics [7]. The amount of adsorption onto activated carbon could be computed by using continuously stirred tank reactor (CSTR) model and plug-flow reactor (PFR) model, both of which are based on the homogeneous surface diffusion model (HSDM) [8,9,10,11]. Campos *et al*. [12, 13] proposed a mathematical model to predict the removal of organic compounds when PAC was applied to various membrane reactor configurations and operations. Their model predictions were based on a single set of equilibrium assumed to occur by homogeneous surface diffusion. The adsorption equilibrium was described with the Freundlich isotherm. Kim *et al*. [4] also assumed a first-order driving force model to simulate the organic removal efficiency of a PAC-MF system. Besides, Chang *et al*. [14] have developed a model, which focused on modeling of organics removal using a PAC-submerged membrane system with PAC initially dosed to the reactor. They identified that the PAC load was an important process parameter for the "PAC initially dosed mode".

However, all the earlier studies considered only the adsorption aspect but they did not incorporate influent characteristics or membrane properties in the modeling. Vigneswaran, *et al*. [7] developed a simple mathematical model for SMAHS using the concept of CSTR. In their study, the effect of membrane was introduced using the membrane packing density (A_M/V_M) and membrane correlation coefficient (MCC). Since the filtration flux was very low, the flux decline was negligible and not considered in this model.

The objective of this study is to verify the model using detailed experiments at varying operation conditions such as filtration flux, initial PAC dose, preadsorption duration etc. Model predictions are based on adsorption equilibrium and kinetic parameters determined from isotherm and batch experiments respectively.

Mathematical Modeling of Membrane Adsorption Hybrid System

The material balance of organic matter concentration in the SMAHS can be described by Eq. (1)

$$\frac{dC_b}{dt} = \frac{Q}{V} \cdot (C_o - C_b) - \frac{M}{V} \cdot \frac{dq}{dt} - \frac{A_M}{V_M} \cdot MCC \cdot C_b \qquad (1)$$

Where, C_b = the organic concentration in the bulk phase in the reactor (mg/L); Q = the flow rate (m^3/s); V = the volume of the bulk solution in the reactor (m^3); C_o = the organic concentration in the feeding tank (mg/L); M = the weight of PAC used (g); A_M = the surface area of the membrane (m^2); V_M = the volume of membrane (m^3); MCC = the membrane correlation coefficient. [(M/V)·(dq/dt)] represents the adsorption of the organics onto PAC in suspension, and [(A_M/V_M)·MCC·C_b] describes the adsorption onto the PAC layer deposited onto membrane surface. The membrane correlation coefficient (MCC) is an empirical coefficient that combines adsorption of organics on membrane surface and retention of PAC on membrane (associated with organics adsorbed on it).

The model was tested for various parameters such as MCC, solid mass transfer coefficient, filtration flux and influent organic concentration. The performance of the model was found to depend mainly on MCC and the filtration flux. The higher the value of MCC, the better the organic removal efficiency of the membrane hybrid system is. The organic removal efficiency of the system decreased with the increase of filtration flux. The model was sensitive neither to the solid mass transfer coefficient (k_s) nor to the influent organic concentration (Co) within a wide range of organics found in biologically treated sewage effluent [7].

The adsorption equilibrium was quantified based on Talu model [15]. The Talu model takes into account of three main characteristics of the adsorption system, namely chemical equilibria, equation of state (EOS) and phase equilibrium. Chemical equilibria and EOS describe the behavior of the surface phase, and the phase equilibrium links the surface phase properties to bulk phase properties. The mathematical representation of the Talu model is shown in Eqs. 2-4.

$$C_e = \frac{H\Psi \cdot \exp\left(\frac{\Psi}{q_e}\right)}{(1 + K\Psi)} \quad (2)$$

$$\Psi = \left(\frac{-1 + (1 + 4K\zeta)^{0.5}}{2K}\right) \quad (3)$$

$$\zeta = \frac{q_e q}{q_e - q} = \Psi(1 + K\Psi) \quad (4)$$

Here, C_e = Equilibrium organic concentration, mg/L; H = Adsorption constant (Henry's Law); K = Reaction constant; q_e= Saturation amount of organic adsorbed, mg/g; ψ = Organic concentration spreading parameter; and q = measured amount of organic matter adsorbed onto a unit amount of adsorbent, mg/g.

The homogeneous surface diffusion model (HSDM) has been used to study the PAC adsorption kinetics (Eqs. 5-8). HSDM consists of a three-step process [8]: (i) the adsorbate diffuses through a stagnant liquid film layer surrounding the carbon particle; (ii) the adsorbate adsorbs from the liquid phase onto the outer surface of the carbon particle; (iii) the adsorbate diffuses along the inner surface of the carbon particles until it reaches its adsorption site.

$$\frac{\partial q_t}{\partial t} = D_s\left(\frac{\partial^2 q_t}{\partial r^2} + \frac{2}{r}\frac{\partial q_t}{\partial r}\right) \quad (5)$$

The initial and Boundary Conditions are:

$$t = 0 \ ; \ q_t = 0 \tag{6}$$

$$r = 0 \ ; \ \frac{\partial q_t}{\partial r} = 0 \tag{7}$$

$$r = r_p \ ; \ D_s \rho_p \frac{\partial q_t}{\partial r} = k_f \left(C - C_s \right) \tag{8}$$

Where, q_t = the rate of change of surface concentration with time (t) at any radial distance (r) from the center of the activated carbon particle during adsorption, mg/g; D_s = the surface diffusion coefficient (the rate of diffusion of the target compound along the surface of the carbon), m^2/s; k_f = the external mass transfer coefficient, m/s; ρ_p = apparent density of the activated carbon, kg/m^3.

The SMAHS model was solved numerically by applying the orthogonal collocation method to discretize the equations. The discretization was done for the spatial variable, resulting in a set of time derivative ordinary differential equations (ODEs) for the adsorbate concentration. The resulting sets of ODEs were solved using the subroutine DVODE [16].

2. Experimental

2.1 Synthetic wastewater

The synthetic wastewater used in this study consisted of persistent organic (slowly biodegradable) compounds such as humic acid, tannic acid, lignin, polysaccharide and other high molecular weight carbohydrates. This wastewater represents the biologically treated sewage effluent. The characteristics of the synthetic wastewater used are shown in Table 1. The TOC concentration of the synthetic wastewater is 3.6–

4.2 mg/L and pH is 7.6-7.7. This wastewater composition was first recommended by Seo *et al*. [5].

Table 1 Constituents of the synthetic wastewater

2.2 Adsorption equilibrium

Adsorption equilibria experiments were conducted using 100 ml of synthetic wastewater in flasks. The PAC concentration varied from 0 g/L to 10 g/L. The flasks were shaken continuously for 90 hours at 130 rpm at 25 °C (Ratek platform mixer). Total organic carbon (TOC) was measured using the UV-persulphate TOC analyzer (Dohrmann, Phoenix 8000). PAC was first washed with distilled water then dried at 100°C and desiccated prior to use. The characteristics of PAC used in the experiments are shown in Table 2. The adsorption capacity of PAC was found to be 5.67 $mg_{(TOC)}/g_{(PAC)}$ (with wastewater used in this study).

Table 2 Characteristics of the powdered activated carbon (PAC) used

2.3 Adsorption kinetics

The batch experiments were carried out using 2 L of synthetic wastewater at 25 °C. The PAC doses were 0.5 g/L, 2 g/L and 5 g/L. The stirring speed was maintained at 110 rpm. The samples were mixed with PAC and the amount of adsorption was determined for different contact times.

2.4 Submerged membrane adsorption hybrid system

The schematic diagram of the submerged hollow fiber microfiltration system is shown in Figure 1. A hollow fiber membrane module was used and the characteristics of the hollow fiber membrane module are summarized in Table 3. Synthetic wastewater was pumped into the reactor using a feeding pump controlling the feed rate while the effluent flow rate was controlled by a suction pump. Level sensor was used to control the wastewater volume in reactor. The total volume of the membrane reactor is 6 L. A predetermined amount of PAC was added into the tank to adsorb the dissolved organic substances. A pressure gauge was used to measure the transmembrane pressure (TMP) and a soaker hose air diffuser was used to maintain a high air flow rate. The air bubbling in this system has functions of sweeping the membrane surface and mixing the PAC in SMAHS. In the long-term experiments, the air bubbles will also help in supplying oxygen to biological activity.

Table 3 Characteristics of the hollow fiber membrane module used

Figure 1 Experimental set-up of SMAHS

3. Results and discussion

3.1 Adsorption equilibrium

The Talu model described well the adsorption equilibrium behavior of PAC for the synthetic wastewater used in this study. The adsorption equilibrium experimental results and the Talu model prediction are shown in Figure 2. The isotherm parameters q_e, K, H and R^2 of the synthetic wastewater were computed as 37.98 mg/g, 0.20, 0.43 and 0.977 respectively.

Figure 2 Adsorption isotherm of synthetic wastewater (initial TOC = 3.8691 mg/L)

3.2 Adsorption kinetics

In the adsorption kinetics experiments, the TOC removal efficiency of PAC increased by approximately 15 % when PAC dose was increased nearly in proportion by 15% from either 0.5 to 2 g/L or from 2 to 5 g/L (Figure 3). As shown in Figure 3, the prediction curve fitted well with the experimental values. The values of the surface diffusion coefficient D_s and the external mass transfer coefficient k_f calculated for different doses of PAC are summarized in Table 4.

Table 4 Mass transfer coefficients in synthetic wastewater at different doses of PAC (initial TOC = 3.6288 mg/L; stirring speed 110 rpm)

Figure 3 Adsorption kinetics of synthetic wastewater at different doses of PAC (initial TOC = 3.6288 mg/L; stirring speed 110 rpm; C = effluent TOC concentration, mg/L and Co = influent TOC concentration, mg/L)

3.3 Submerged membrane adsorption hybrid system (SMAHS)

3.3.1 Effect of Preadsorption duration

The effect of the duration of preadsorption was observed over the ten-hour experiments at a filtration flux 48 $L/m^2.h$. The PAC dose and the aeration rate were maintained at 5 g/L and 9.6 $m^3/h.m^2_{(membrane\ area)}$ respectively. The TOC removal efficiency was slightly higher (83.5%) in the case of no preadsorption (Figure 4). However, as shown in Figure 5, without preadsorption, the TMP development through membrane increased by 50 kPa within 10 hours. In the case of no preadsorption, the initial organic loading onto membrane surface was higher that could cause initial irreversible fouling of the membrane. Thus, preadsorption can reduce the membrane fouling by reducing the organic concentration exposed to the membrane surface. One-hour preadsorption was found to be sufficient as it produced much lower TMP development and comparable TOC removal (as compared to two-hour preadsorption).

When a longer duration of preadsorption was used (i.e. 2 hours), the carbon removed the majority of organics during the first two hours of operation. It left less adsorption sites on the carbon for further removing the organic matter when the membrane filtration was started at the beginning of 3rd hour. As can be seen from Figure 6, after 3 hours run, the TOC removal efficiency of PAC with 1-hour preadsorption declined slower than that with 2-hour preadsorption. Therefore, in the subsequent experiments, one-hour preadsorption was used as an operation condition to mitigate membrane fouling phenomenon. The modeling simulation of effluent concentration and model parameters are presented in Figures 7.a–7.c and Table 5 respectively.

Figure 4 TOC removal efficiency of effluent at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC dose = 5 g/L; aeration rate = 8 L/min)

Figure 5 TMP profile at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC dose = 5 g/L; aeration rate = 8 L/min)

Figure 6 TOC removal efficiency of PAC in PAC-MF reactor at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC dose = 5 g/L; aeration rate = 8 L/min)

Figure 7 Model prediction of effluent concentration at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC = 5 g/L; aeration rate = 8 L/min)

Table 5 The modeling parameters of SMAHS at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC = 5 g/L; aeration rate = 8 L/min)

3.3.2 Effect of Aeration Rate

Aeration rate was varied from 8 L/min to 20 L/min to study the effect of aeration rates. Figures 8.a–8.d and 9 show both the experimental results and the model simulation. The results show that all of the coefficients (Ds, k_f and MCC) increased rapidly as aeration rate was increased from 8 L/min to 16 L/min. The increase of these coefficients was slowed down when the aeration rate increased from 16 L/min to 20 L/min. Similarly, there was an increase in removal efficiency with the increase in aeration rate (8 to 16 L/min). The efficiency could not be improved with any further increase in aeration rate from 16 (87.28% removal efficiency) to 20 L/min(86.85% removal efficiency) (Figure 10). Hence, an aeration rate of 16 L/min was considered as the optimum value in this study.

Figure 8 Model prediction of effluent concentration at different aeration rates (filtration flux = 48 L/m^2.h; PAC = 5 g/L; preadsorption = 1 hour)

Figure 9 Variation of the model parameters of SMAHS at different aeration rates (filtration flux = 48 L/m^2.h; PAC = 5 g/L; Preadsorption = 1 hour)

Figure 10 TOC removal efficiency at different aeration rates (filtration flux = 48 L/m^2.h; PAC dose = 5 g/L; preadsorption = 1 hour)

3.3.3 Effect of Backwash Frequency

The effect of backwash frequency was studied to see whether it has any effect on organic removal or on the TMP development. Two representative backwash frequencies were chosen from preliminary experiments (1 minute backwash after every 59 minutes and 30 seconds backwash after every 29.5 minutes of filtration). From Figure 11, it is clear that the removal efficiencies in terms of TOC were not much different between the two backwash frequencies studied. A 30-second backwash after every 29.5 minutes filtration gave slightly better TOC removal (85.3%) than that with 1 minute backwash after 59 min of filtration (82.9%). Moreover, there was no obvious difference of the TMP development between the two backwash conditions (Figure 12). Thus, 1 minute backwash during each hour of filtration was selected in the subsequent experiments.

Figure 11 TOC removal efficiency at different backwash frequencies (filtration flux = 48 L/m^2.h; PAC dose = 2 g/L; preadsorption = 1 hour; aeration rate = 16 L/min)

Figure 12 TMP profile at different backwash frequencies (filtration flux = 48 L/m^2.h; PAC dose = 2 g/L; preadsorption = 1 hour; aeration rate = 16 L/min)

3.3.4 Effect of PAC Dose

The effect of PAC dosage was studied in terms of TOC removal and TMP development (Figure 13). Figure 13 shows the model simulation results and the model parameters are summarized in Table 6. The external mass transfer coefficient k_f and membrane correlation coefficient MCC increased with the increase in PAC dose. The surface diffusion coefficient D_s was the highest at PAC dose of 5 g/L PAC. There was no noticeable difference of organic removal when PAC dose increased from 2 g/L to 10 g/L. However, higher PAC dose could reduce the TMP development which is helpful in preventing membrane clogging (Figure 14). A long-term study (PAC dose = 5 g/L; filtration flux = 12 $L/m^2.h$; aeration rate = 14.4 $m^3/h.m^2_{(membrane\ area)}$; backwash frequency = 1 day; backwash duration = 2 mins; backwash rate = 2.5 times of filtration flux) conducted by the authors indicated that the TOC removal efficiency could keep consistently more or less 84.1% even after 15 days of operation. It is noted that an addition of 5 g/L PAC was made initially with a daily replacement of 2.5% of total amount PAC in this case. It works out to be carbon dose of 70g/m^3 of treated water. This calculation assumed only 15 days of operation, but in real situation, it can operate for several months due to the biological degradation of organic matter adsorbed onto PAC.

Figure 13 Model prediction of organic removal at different PAC doses (filtration flux = 48 $L/m^2.h$; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 120 $L/m^2.h$; C = effluent TOC concentration, mg/L and Co = influent TOC concentration, mg/L)

Table 6 The modeling parameters of SMAHS at different PAC doses (filtration flux = 48 $L/m^2.h$; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 120 $L/m^2.h$)

Figure 14 Effect of PAC dose on the TMP development (filtration flux = 48 $L/m^2.h$; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1 min; backwash rate = 120 $L/m^2.h$)

3.3.5 Effect of Filtration flux

The effect of filtration flux was studied by varying the filtration flux in the range of 24–48 L/m^2.h (Figures 15 and 16). The model prediction and parameters are presented in Figure 15 and Table 7 respectively. The surface diffusion coefficient D_s and membrane correlation coefficient MCC were highest at the lowest filtration flux of 24 L/m^2.h. The value of external mass transfer coefficient k_f decreased with the increase in filtration flux. As expected, the lower filtration flux led to the highest TOC removal and the lowest TMP development. The average TOC removal efficiencies were 89.8%, 88.6% and 83.2% (over the filtration time of 600 minutes) at the filtration fluxes of 24 L/m^2.h, 36 L/m^2.L and 48 L/m^2.h respectively.

Figure 15 Model prediction of organic removal at different filtration flux (PAC dose = 5 g/L; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 2.5 times of filtration flux; C = effluent TOC concentration, mg/L and Co = influent TOC concentration, mg/L)

Figure 16 Effect of different filtration flux on the TMP development (PAC dose = 5 g/L; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 2.5 times of filtration flux)

Table 7 The modeling parameters of SMAHS at different filtration flux (PAC dose = 5 g/L; aeration rate = 16 L/min; preadsorption = 1 hour; backwash frequency = 1 hour; backwash duration = 1 min; backwash rate = 2.5 times of filtration flux)

4. Conclusion

The submerged membrane adsorption hybrid system (SMAHS) was effective in removing dissolved organic matter from the synthetic wastewater (which represents the secondary sewage effluent contains persisting organic pollutants). The preadsorption, PAC dose, aeration rate and filtration flux had effects both on organic matter removal efficiency and TMP development. It indicates significantly the need in optimizing these parameters with the specific water to be treated and the characteristics of PAC chosen. The semi-empirical mathematical model was successful in describing the adsorption of organic matter onto the PAC as well as the effluent concentration of the membrane-adsorption system. The membrane correlation coefficient (MCC) is an empirical parameter in the model. The higher the MCC value, the better the organic removal efficiency was. The preadsorption of 1 hour prior to the membrane operation was important in mitigating the membrane fouling. The values of external mass transfer coefficient k_f and membrane correlation coefficient MCC increased with the increase in PAC dose. The surface diffusion coefficient Ds was highest at PAC of 5 g/L. The surface diffusion coefficient D_s and MCC reached to the highest value at the lowest filtration flux of 24 $L/m^2.h$. Although the proposed model enables to predict well the organic removal efficiency of the SMAHS for the short-term experiments, it is necessary to incorporate a biological component in equation in order to predict the long-term efficiency of SMAHS where biological degradation of organics is a major factor.

5. List of Symbols

Nomenclature

A_M the surface area of the membrane (m^2)

C_o the organic concentration in the feeding tank (mg/L)

C_b the organic concentration in the bulk phase in the reactor (mg/L)

C_e equilibrium organic concentration (mg/L)

D_s the surface diffusion coefficient (m^2/s)

H adsorption constant (Henry's Law)

K reaction constant

k_f the external mass transfer coefficient (m/s)

k_s the solid mass transfer coefficient

Q the flow rate (m^3/s)

V the volume of the bulk solution in the reactor (m^3)

M the weight of PAC used (g)

q measured amount of organic matter adsorbed onto a unit amount of adsorbent (mg/g)

q_e saturation amount of organic adsorbed (mg/g)

q_t the rate of change of surface concentration with time (t) at any radial distance (r) from the center of the activated carbon particle during adsorption (mg/g)

V_M the volume of membrane (m^3)

MCC the membrane correlation coefficient

$[(M/V)\cdot(dq/dt)]$ represents the adsorption of the organics onto PAC in suspension

$[(A_M/V_M)\cdot MCC\cdot C_b]$ describes the adsorption onto the PAC layer deposited onto membrane surface

Greek letters

ζ parameter ($=\Psi(1+K\Psi)$)

ψ organic concentration spreading parameter

ρ_p = apparent density of the activated carbon (kg/m^3)

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Table 1
Constituents of the synthetic wastewater

Compounds	Weight (mg/L)
Beef Extract	1.8
Peptone	2.7
Humic acid	4.2
Tannic acid	4.2
(Sodium) lignin sulfonate	2.4
Sodium lauryle sulphate	0.94
Acacia gum powder	4.7
Arabic acid (polysaccharide)	5
$(NH_4)_2SO_4$	7.1
KH_2PO_4	7.0
NH_4HCO_3	19.8
$MgSO_4.3H_2O$	0.71

Table 2
Characteristics of the powdered activated carbon (PAC) used

Specification	PAC-WB
Iodine number (mg/g min)	900
Ash content (%)	6 max.
Moisture content (%)	5 max.
Bulk density (kg/m^3)	290-390
Surface area (m^2/g)	882
Nominal size	80% min finer than 75 micron
Type	Wood based
Mean pore diameter (Å)	30.61
Micropore volumn (cc/g)	0.34
Mean diameter (µm)	19.71
Product code	MD3545WB powder

Table 3
Characteristics of the hollow fiber membrane module used

Item	Characteristics
Material	Hydrophilic polyethylene
Nominal pore size	0.1 μm
Outer diameter	0.41 mm
Inner diameter	0.27 mm
No. of fiber	320 (16×20)
Length of fiber	12 cm
Surface area	0.05 m^2
Membrane packing density	9858 m^2/m^3
Membrane manufacturer	Mitsubishi-Rayon, Tokyo, Japan

Table 4
Mass transfer coefficients in synthetic wastewater at different doses of PAC (initial TOC = 3.6288 mg/L; stirring speed 110 rpm)

PAC dose (g/L)	Ds (m^2/s)	k_f (m/s)
0.5	7.498×10^{-15}	3.992×10^{-7}
2	4.366×10^{-15}	2.304×10^{-7}
5	2.262×10^{-15}	1.163×10^{-7}

Table 5
The modeling parameters of SMAHS at different preadsorption durations
(filtration flux = 48 $L/m^2.h$; PAC = 5 g/L; aeration rate = 8 L/min)

Item	No preadsorption	1-hour preadsorption	2-hour preadsorption
Average influent TOC, mg/L	3.8423	3.5358	3.6566
Pre-adsorbed amount, mg/g	-	0.4713	0.5439
Ds (m^2/s)	2.316×10^{-14}	1.302×10^{-14}	7.390×10^{-15}
k_f (m/s)	8.461×10^{-9}	1.282×10^{-8}	1.843×10^{-8}
Membrane coefficient (MCC), m/s	1.448×10^{-8}	6.420×10^{-9}	1.048×10^{-8}

Table 6

The modeling parameters of SMAHS at different PAC doses (filtration flux = 48 L/m^2.h; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 120 L/m^2.h)

Item	PAC dose 2 g/L	PAC dose 5 g/L	PAC dose 10 g/L
Average influent TOC, mg/L	3.8562	3.7321	3.8717
Pre-adsorbed amount, mg/g	1.3232	0.5602	0.2535
Ds (m^2/s)	1.365×10^{-14}	1.775×10^{-14}	1.187×10^{-15}
k_f (m/s)	5.558×10^{-9}	2.404×10^{-8}	5.666×10^{-8}
Membrane coefficient (MCC), m/s	6.251×10^{-9}	2.780×10^{-8}	5.373×10^{-8}

Table 7
The modeling parameters of SMAHS at different filtration flux (PAC dose = 5 g/L; aeration rate = 16 L/min; preadsorption = 1 hour; backwash frequency = 1 hour; backwash duration = 1 min; backwash rate = 2.5 times of filtration flux)

Item	24 $L/m^2.h$	36 $L/m^2.h$	48 $L/m^2.h$
Average influent TOC, mg/L	3.9601	3.7362	3.7321
Pre-adsorbed amount, mg/g	0.6744	0.6491	0.5602
Ds (m^2/s)	2.637×10^{-14}	2.548×10^{-14}	1.775×10^{-14}
k_f (m/s)	4.397×10^{-8}	5.031×10^{-8}	2.404×10^{-8}
Membrane coefficient (MCC), m/s	6.876×10^{-8}	5.005×10^{-8}	2.780×10^{-8}

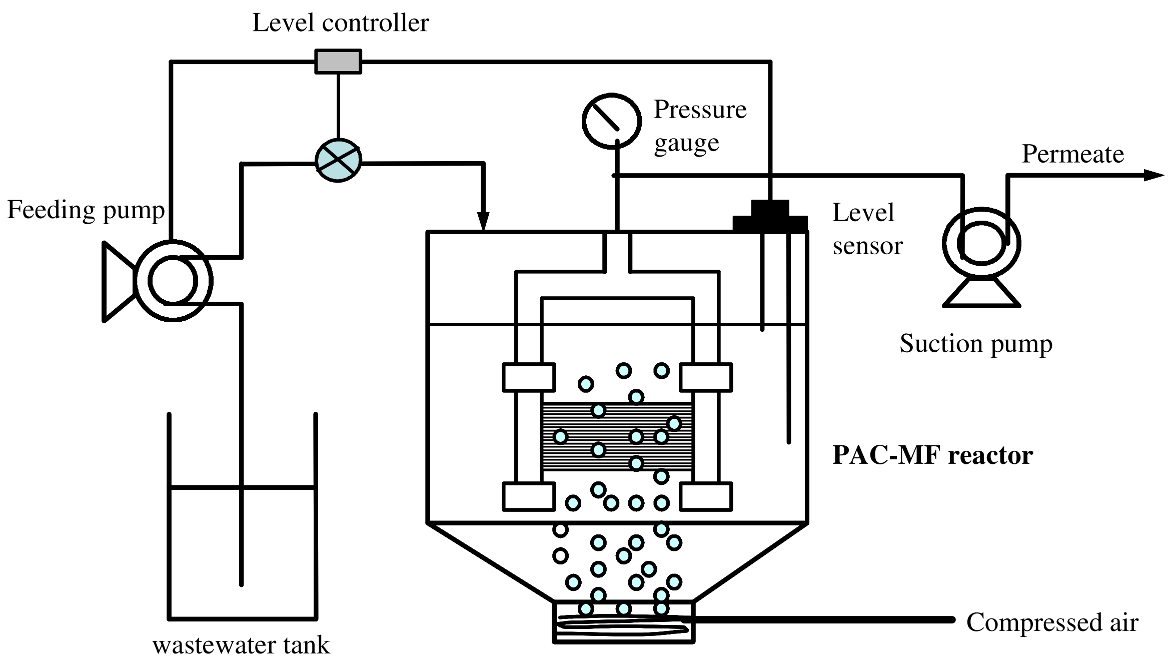


Figure 1 Experimental set-up of SMAHS

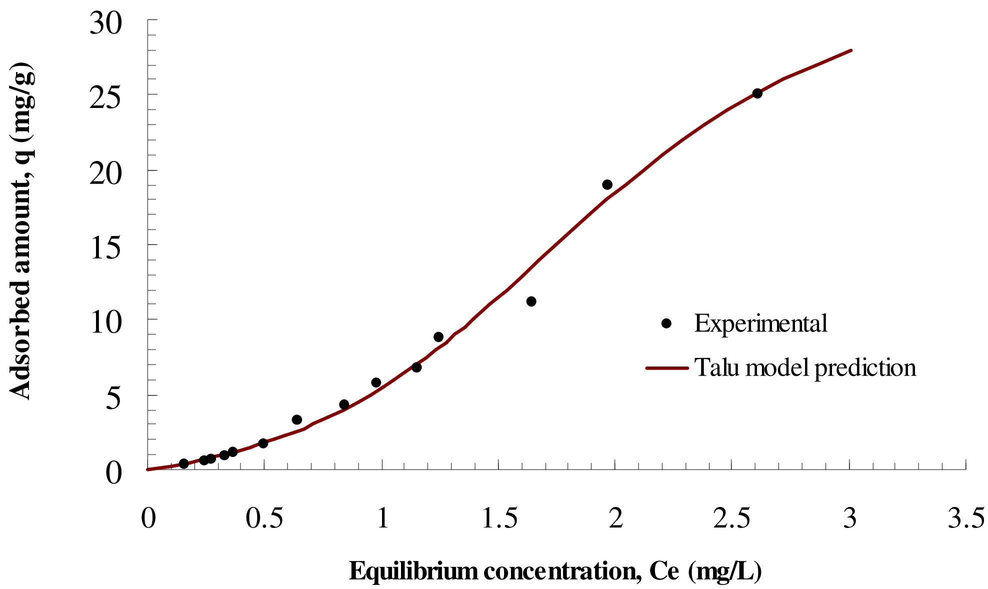


Figure 2 Adsorption isotherm of synthetic wastewater (initial TOC = 3.8691 mg/L)

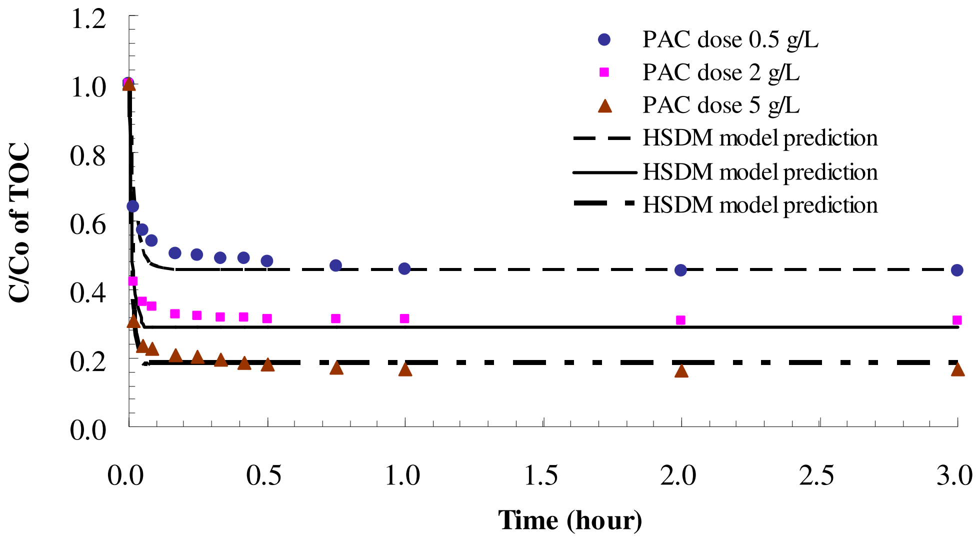


Figure 3 Adsorption kinetics of synthetic wastewater at different doses of PAC (initial TOC = 3.6288 mg/L; stirring speed 110 rpm; C = effluent TOC concentration, mg/L and Co = influent TOC concentration, mg/L)

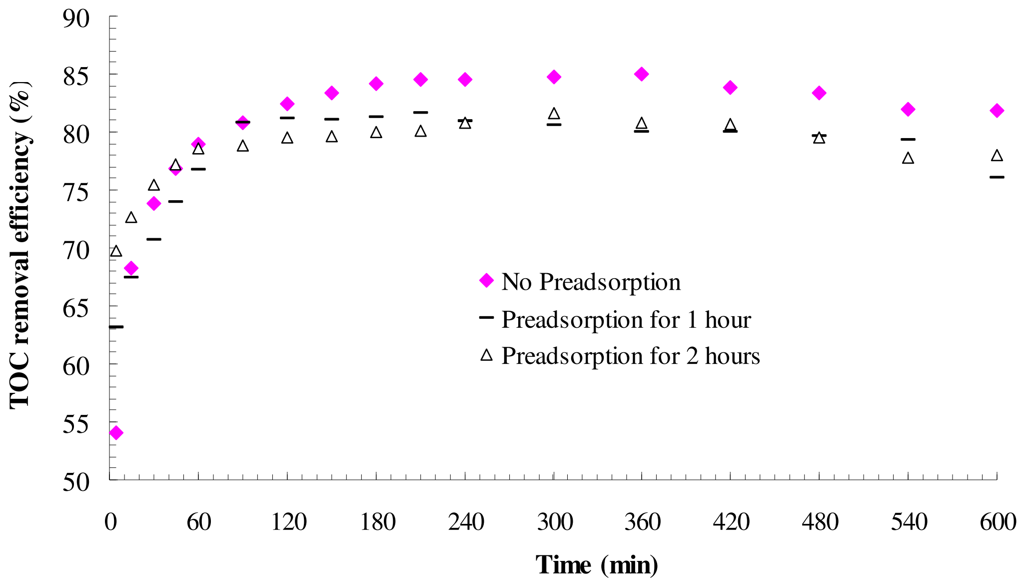


Figure 4 TOC removal efficiency of effluent at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC dose = 5 g/L; aeration rate = 8 L/min)

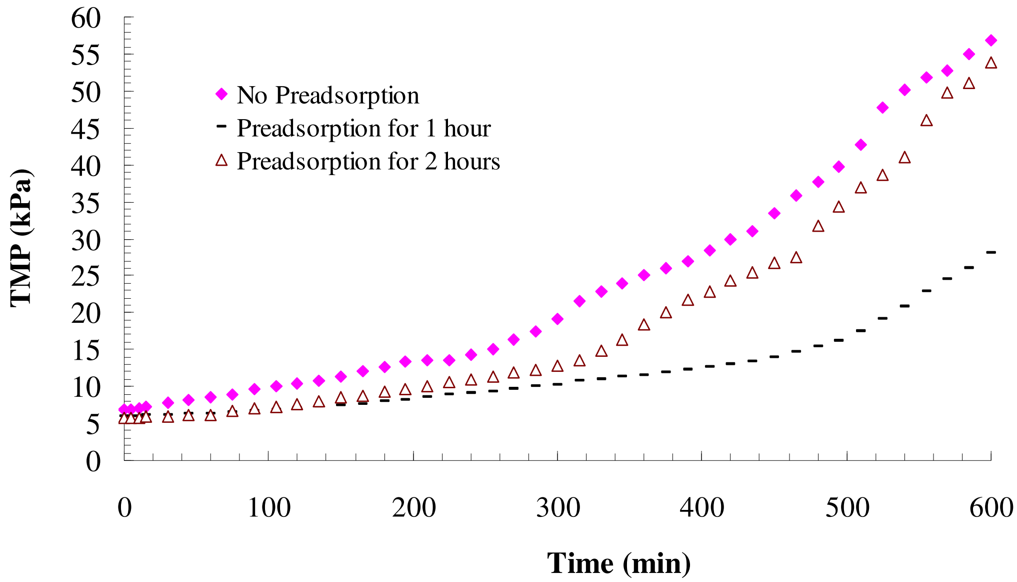


Figure 5 TMP profile at different durations of preadsorption
(filtration flux = 48 L/m^2.h; PAC dose = 5 g/L; aeration rate = 8 L/min)

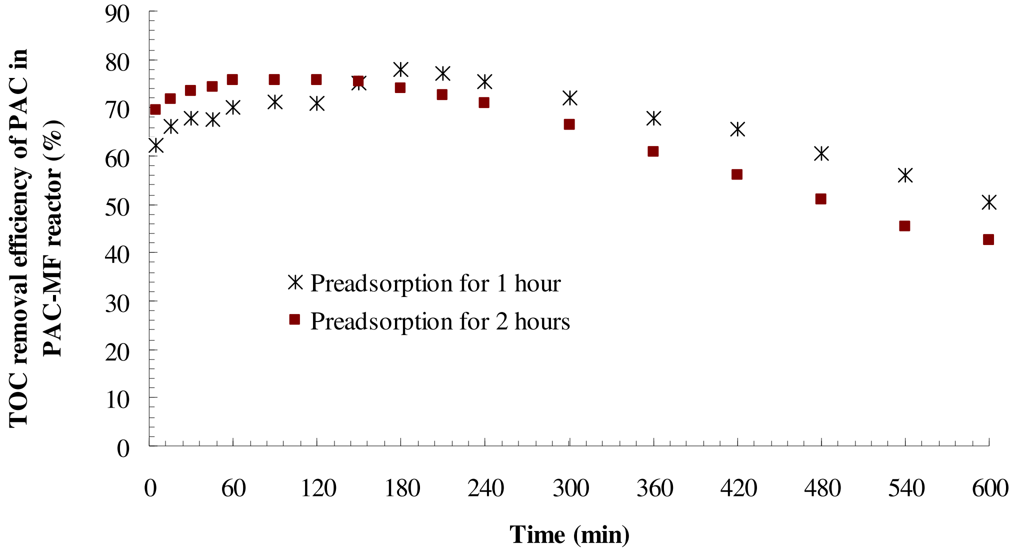
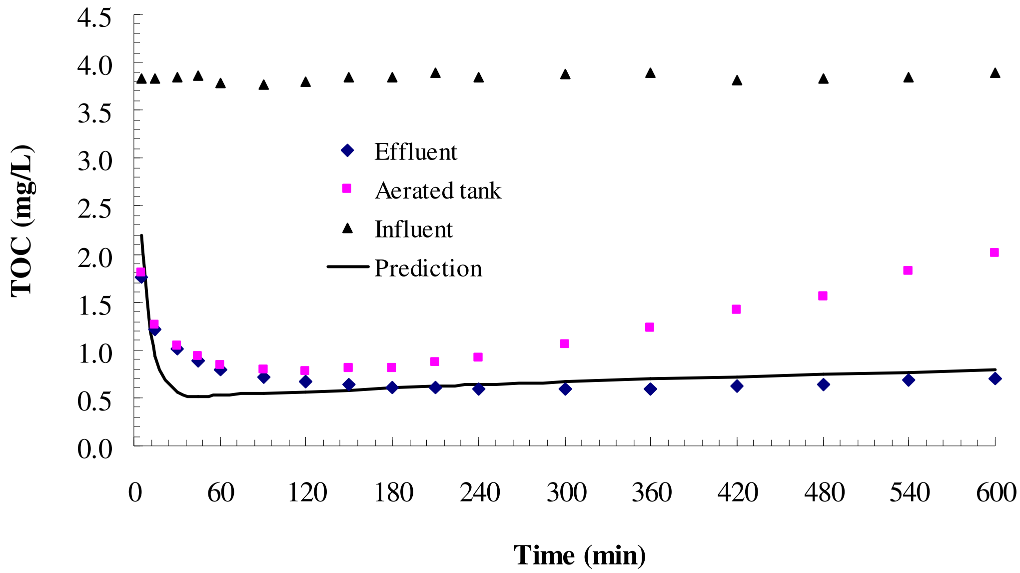
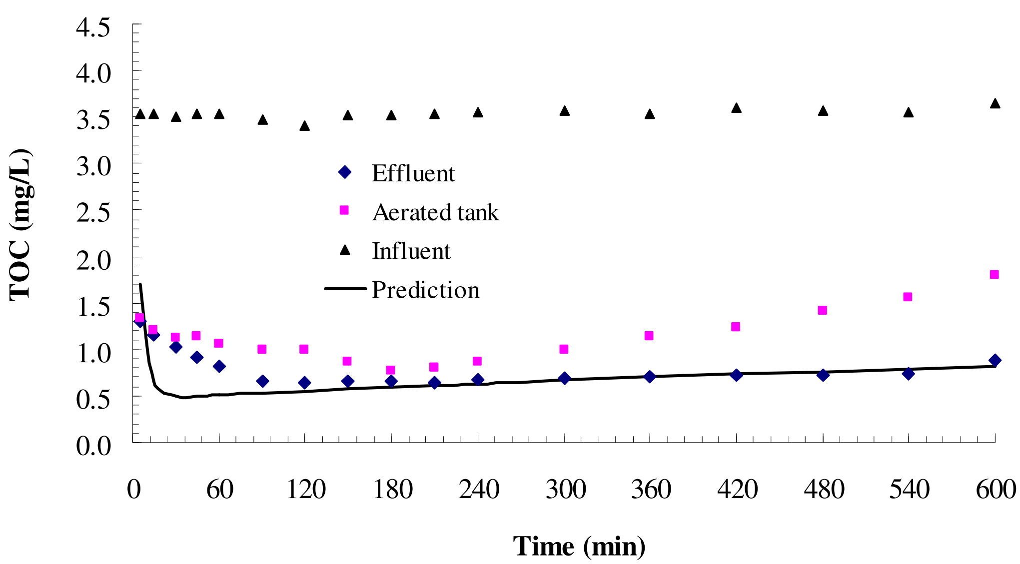


Figure 6 TOC removal efficiency of PAC in PAC-MF reactor at different durations of preadsorption (filtration flux = 48 $L/m^2.h$; PAC dose = 5 g/L; aeration rate = 8 L/min)

(a) Without preadsorption



(b) 1-hour preadsorption



(c) 2-hour preadsorption

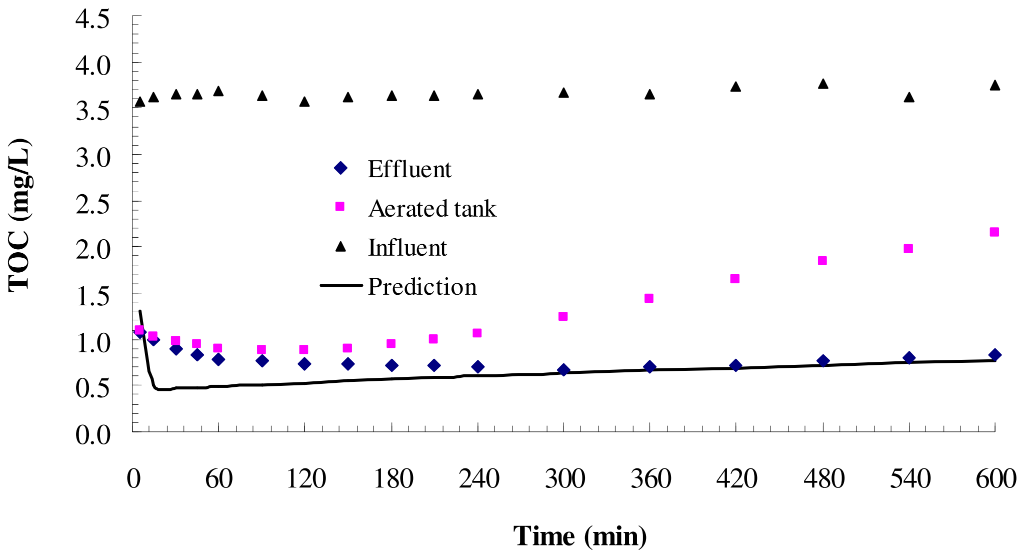
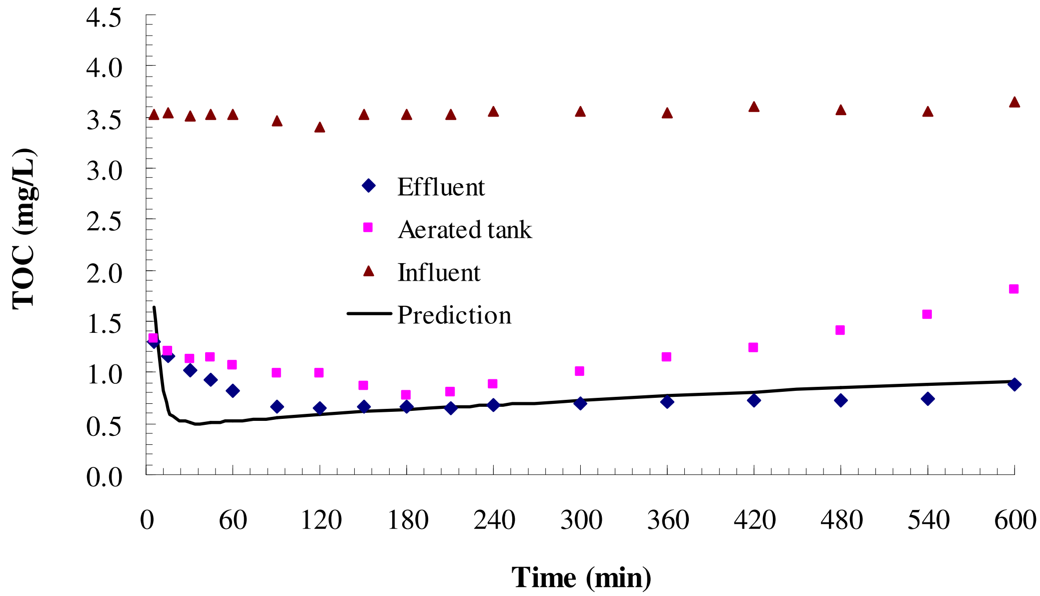
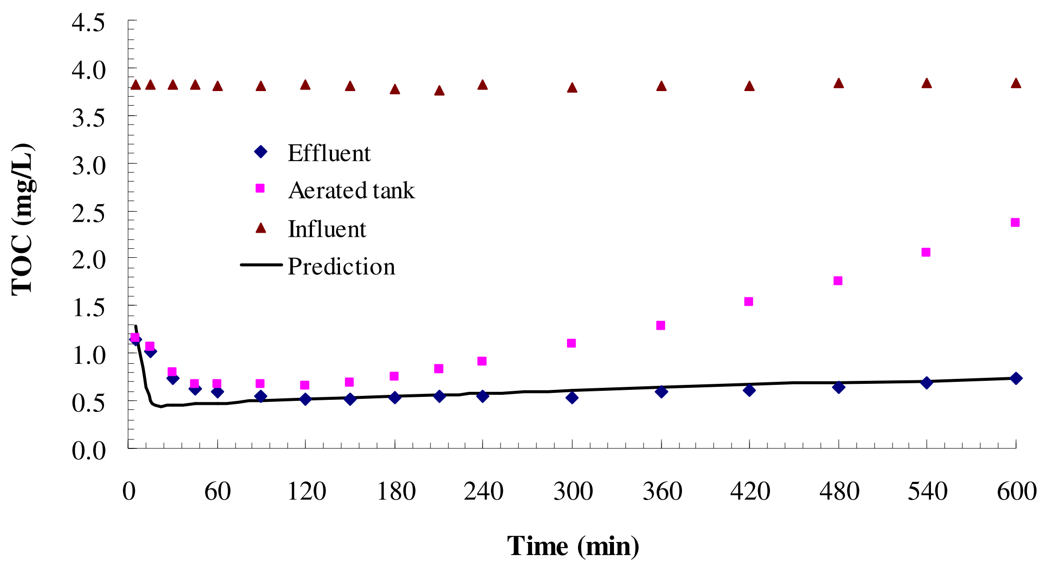


Figure 7 Model prediction of effluent concentration at different durations of preadsorption (filtration flux = 48 L/m^2.h; PAC = 5 g/L; aeration rate = 8 L/min)

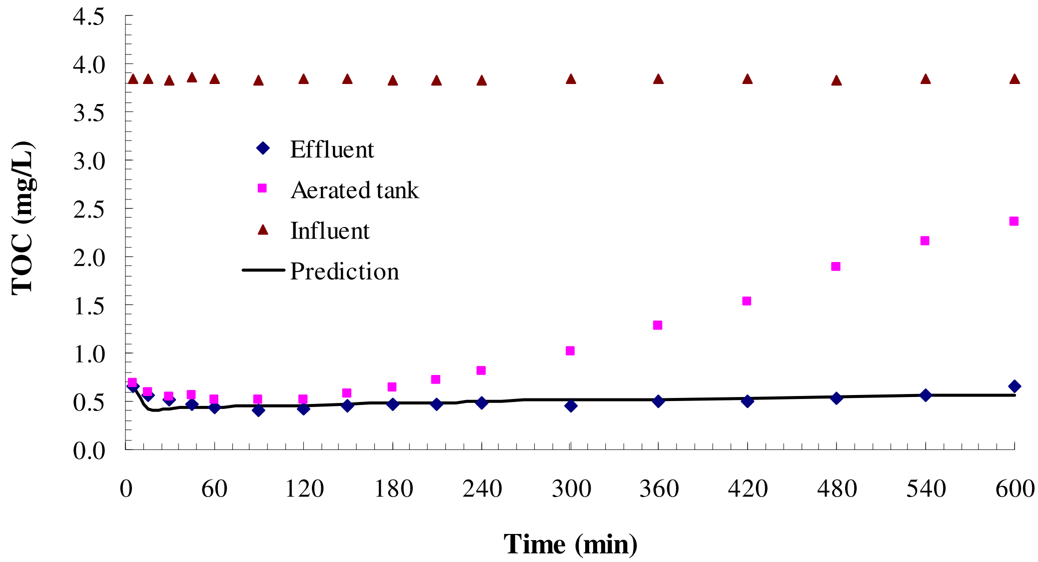
(a) Aeration rate 8 L/min



(b) Aeration rate 12 L/min



(c) Aeration rate 16 L/min



(d) Aeration rate 20 L/min

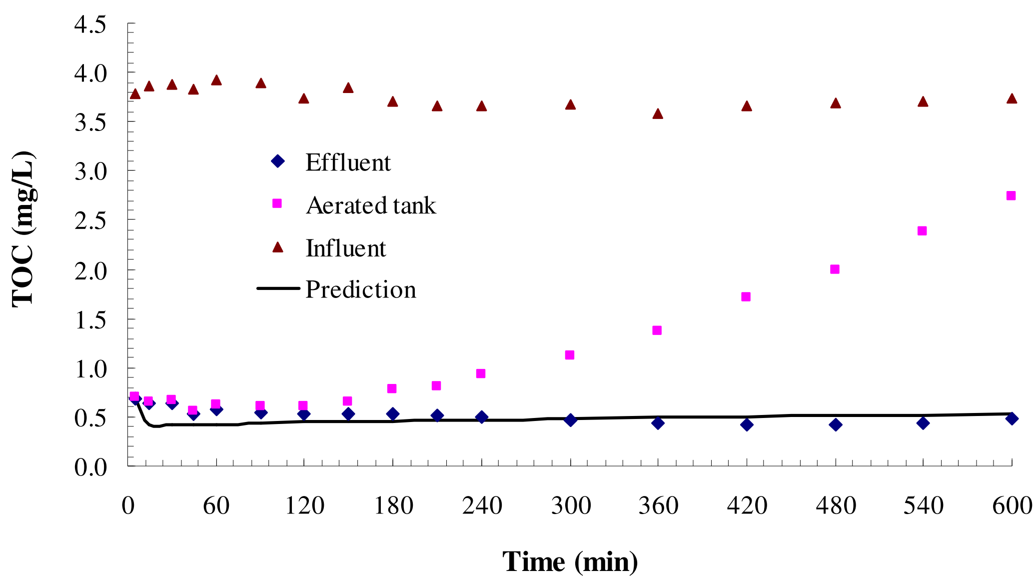


Figure 8 Model prediction of effluent concentration at different aeration rates (filtration flux = 48 $L/m^2.h$; PAC = 5 g/L; preadsorption = 1 hour)

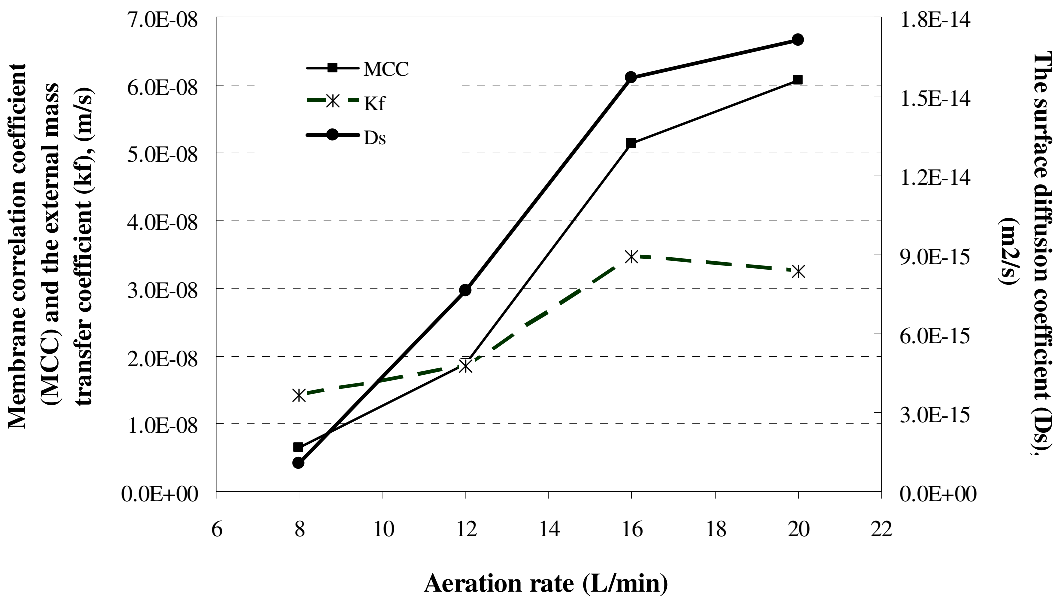


Figure 9 Variation of the model parameters of SMAHS at different aeration rates (filtration flux = 48 $L/m^2.h$; PAC = 5 g/L; Preadsorption = 1 hour)

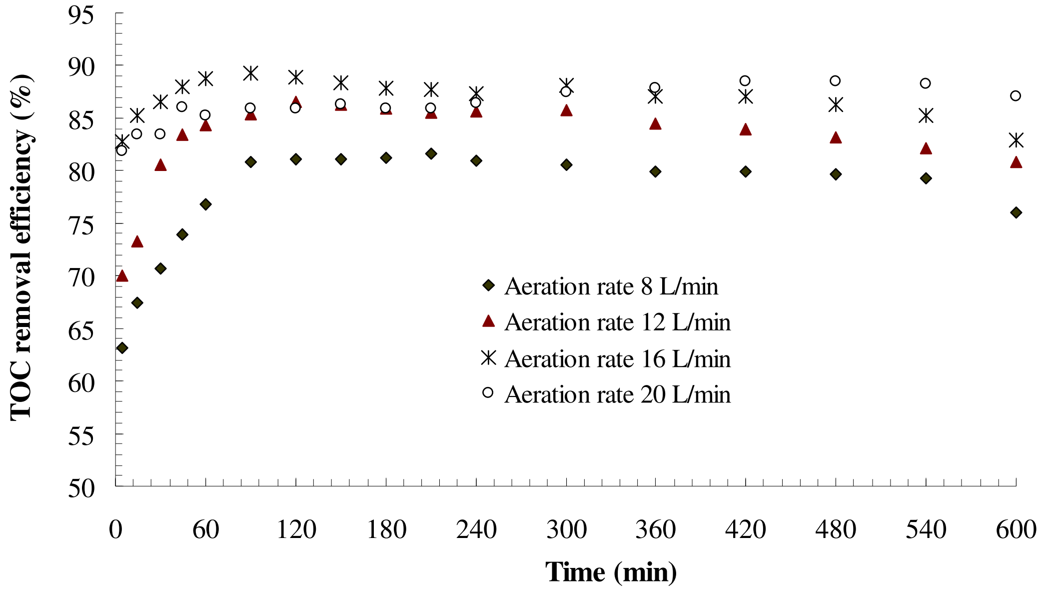


Figure 10 TOC removal efficiency at different aeration rates
(filtration flux = 48 L/m^2.h; PAC dose = 5 g/L; preadsorption = 1 hour)

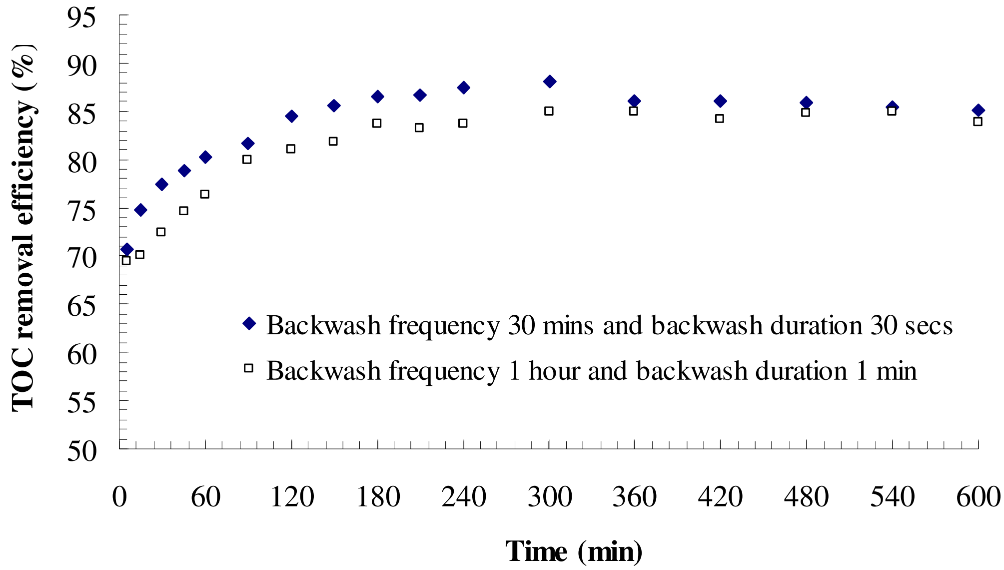


Figure 11 TOC removal efficiency at different backwash frequencies (filtration flux = 48 $L/m^2.h$; PAC dose = 2 g/L; preadsorption = 1 hour; aeration rate = 16 L/min)

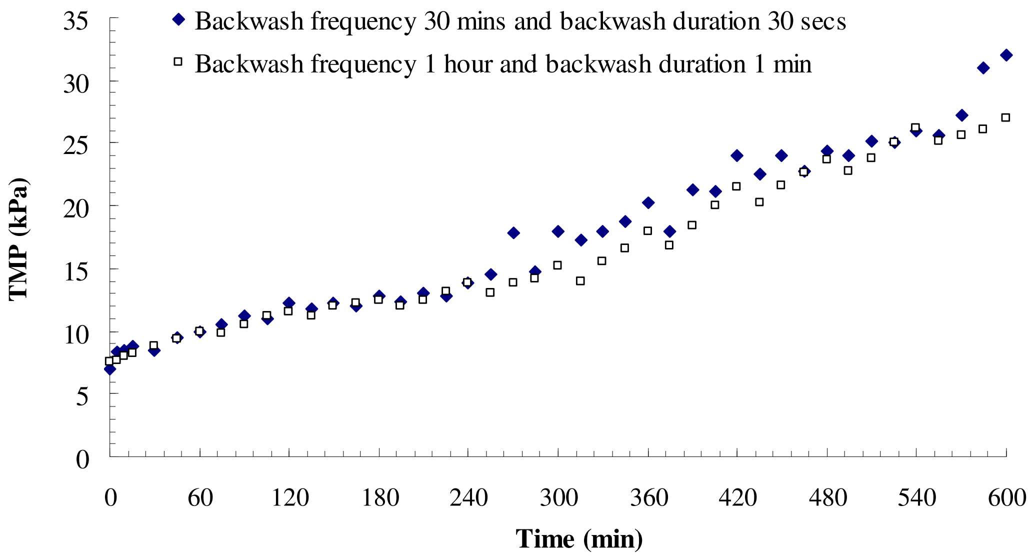


Figure 12 TMP profile at different backwash frequencies (filtration flux = 48 L/m^2.h; PAC dose = 2 g/L; preadsorption = 1 hour; aeration rate = 16 L/min)

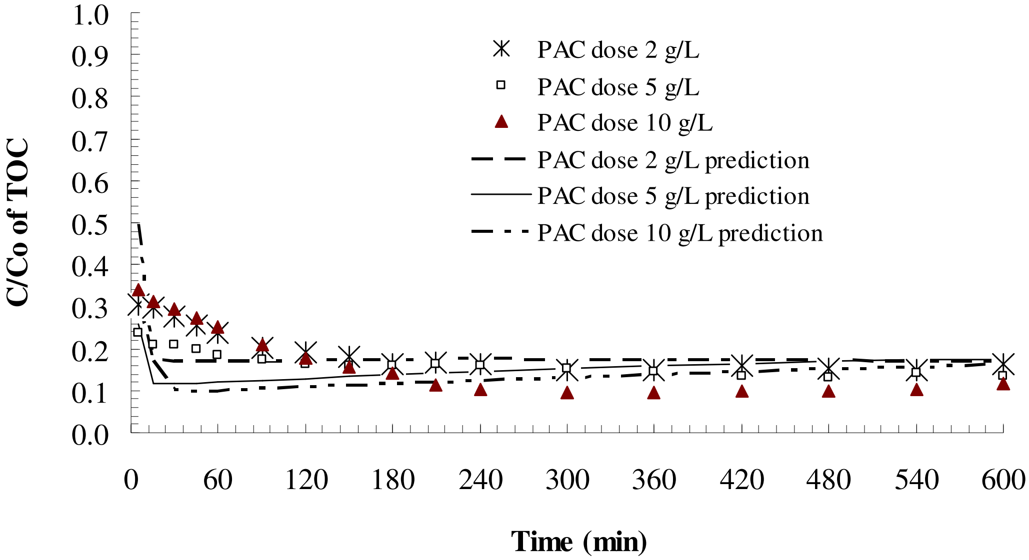


Figure 13 Model prediction of organic removal at different PAC doses (filtration flux = 48 L/m^2.h; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 120 L/m^2.h; C = effluent TOC concentration, mg/L and Co = influent TOC concentration, mg/L)

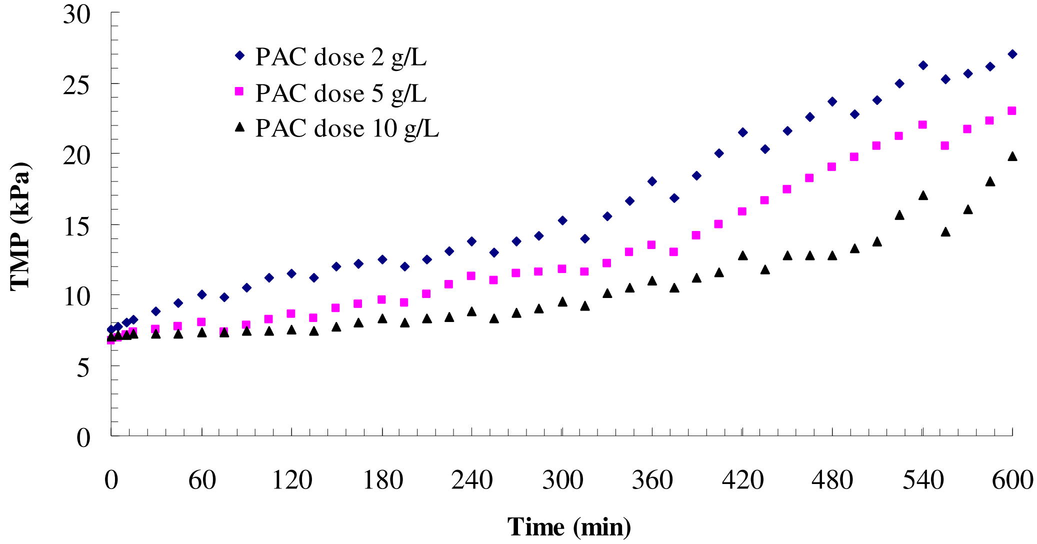


Figure 14 Effect of PAC dose on the TMP development (filtration flux = 48 L/m^2.h; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1 min; backwash rate = 120 L/m^2.h)

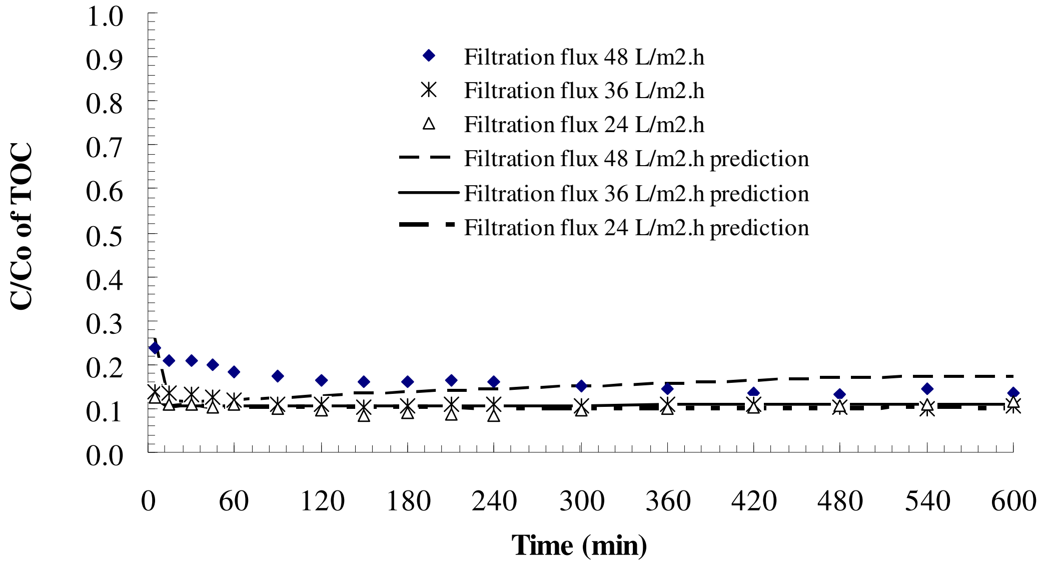


Figure 15 Model prediction of organic removal at different filtration flux (PAC dose = 5 g/L; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 2.5 times of filtration flux; C = effluent TOC concentration, mg/L and Co = influent TOC concentration, mg/L)

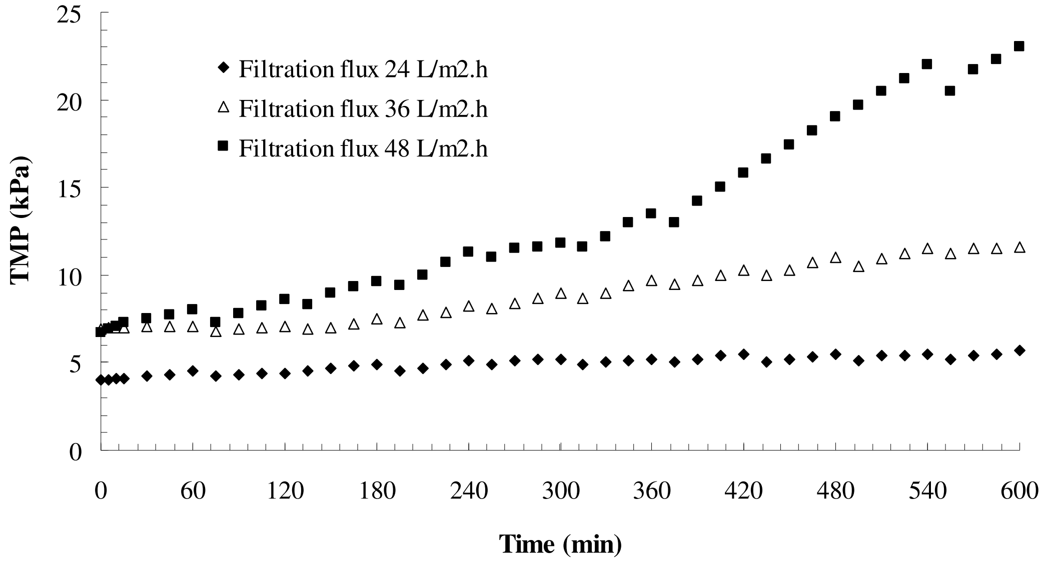


Figure 16 Effect of different filtration flux on the TMP development (PAC dose = 5 g/L; preadsorption = 1 hour; aeration rate = 16 L/min; backwash frequency = 1 hour; backwash duration = 1min; backwash rate = 2.5 times of filtration flux)