Simulation and assessment of sludge concentration and rheology in the process of waste activated sludge treatment

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Abstract

The process of using flat-sheet membrane for simultaneous sludge thickening and digestion (MSTD) was employed. The variations of sludge concentration and rheology were characterized and simulated. Based on mass balance analysis, mathematical models were developed and successfully used to predict and evaluate the variations of sludge concentration and the digestion efficiency in the MSTD process. The apparent viscosity of sludge could be modeled as functions of mixed liquor suspended solids and shear rates. The sludge in the MSTD process showed both shear-thinning and viscoplastic behaviour, and under various shear rates different rheological models could be chosen to predict their flow behaviour. It was also found that sludge concentration and viscosity had significant correlations with membrane fouling in the MSTD process.

Key words: membrane filtration; membrane fouling; sludge thickening; sludge digestion; waste activated sludge

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Introduction

It is widely accepted that conventional activated sludge process is a cost-effective and efficient method for wastewater treatment; however, it produces excess biomass as waste activated sludge (WAS) that is difficult and expensive to handle and dispose of, particularly when wastewater treatment plants (WWTPs) were adapted for biological nutrient removal. Rai et al. (2004) reported that the cost of WAS treatment and disposal accounted up to 60% of the total operating cost in WWTPs. WAS treatment became a more difficult and complex problem in WWTPs attributed to the stringent effluent criteria and restrictions to landfill WAS.

Thickening and dewatering are usually performed for volume reduction of WAS in WWTPs. After thickening, a stabilization step, such as sludge digestion, is practiced to achieve stabilization, detoxification and minimization of WAS, especially for medium and large-scale WWTPs (Zhang et al., 2000). Sludge thickening is generally conducted by physical means, including gravity thickening, dissolved air flotation (DAF) thickening, centrifugal thickening, etc. Among the typical sludge thickening technologies, several problems and disadvantages are existing, e.g., the large footprint and low thickening efficiency and the release of phosphorus under long sludge retention time (SRT) with gravity thickening process, lower quantity of sludge storage and higher energy cost with DAF thickening compared with gravity thickening, and much higher energy cost and advanced maintenance requirements with centrifugal thickening technology (Zhang et al., 2000; Metcalf & Eddy Inc., 2003; Hua et al., 2005).

In order to solve some problems dealing with conventional thickening technologies and to incorporate thickening and digestion into a single reactor, an innovative process of employing flat-sheet membrane for simultaneous sludge thickening and digestion (MSTD) was proposed in our previous research (Wang et al., 2008). The preliminary study demonstrated its feasibility for WAS treatment, in which good sludge thickening and digestion efficiency and superior effluent quality were achieved. Although microfiltration, ultra-filtration, nanofiltration and other processes coupled membrane solid-liquid separation such as membrane bioreactor (MBR) have been intensively studied and widely used for the treatment of municipal wastewater, industrial wastewater and surface water/drinking water in past decades (Mehta and Zydney, 2005; Melin et al., 2006; Kim et al., 2007; Wu et al., 2007), the application of membrane to WAS thickening and digestion is a new attempt and worth investigating.

In this study, specific attention was paid to simulate and assess the variations of sludge concentration and rheology in the membrane for simultaneous sludge thickening...
and digestion (MSTD) process by employing mathematical models. The variations of sludge concentration and the digestion efficiency were predicted and evaluated by mathematical models. Sludge rheology behavior and the characteristics of sludge flow behavior under different shear rates were studied. The results were expected to provide a sound understanding of sludge concentration and rheology variations in MSTD process and to facilitate its design and operation for WAS treatment.

1 Materials and methods

1.1 Operation of MSTD process

A pilot-scale MSTD reactor located at Quyang Municipal Wastewater Treatment Plant (WWTP) in Shanghai, China, was studied. The reactor configuration (Fig. 1) and membrane materials were the same as those reported previously (Wu et al., 2009). Activated sludge was firstly pumped into a sludge storage tank from an aerobic basin of Quyang Municipal WWTP and then fed into the MSTD reactor. The properties of the activated sludge could be found elsewhere (Wu et al., 2009). In order to supply oxygen demanded by the microorganisms and to induce a crossflow velocity (CFV) along the membrane surface, air was provided by a compressor through an air diffuser. The effluent filtered through membrane modules was obtained by suction pumps connected to the modules. The effluent flow rate and transmembrane pressure were monitored. A water level sensor was used for maintaining a constant water level of the MSTD reactor over the experimental period.

When the mixed liquor suspended solids (MLSS) concentration in the MSTD reactor reached approximately 35 g/L, the thickened and digested sludge was drained out while the influent activated sludge and the permeate flow were stopped. After that, the reactor was filled with the fresh activated sludge, and then the next cycle was started.

It was about fifteen days of one cycle from the initial fresh sludge to the final thickened and digested sludge. The sludge retention time (SRT) of the MSTD reactor was 15 d (one cycle), and the hydraulic retention time (HRT) about 1 d. The filtration operation of the pilot-scale MSTD reactor was conducted by pump suction with the constant flow rate (15 L/(m²·h)) of membrane flux (membranes were chemically cleaned with NaClO solution (0.5% (V/V), 2 h duration) every two cycles, i.e., every 30 d to recover their permeability). Intermittent filtration, 10 min filtration and 2 min pause, was carried out during the whole experimental period. The CFV along the membrane surface was maintained at 0.2–0.4 m/s by coarse bubble aeration. When the transmembrane pressure was higher than 30 kPa, chemical cleaning in-place procedure would be performed. The temperature in the MSTD reactor was about 20–23°C during the operation.

1.2 Rheological behavior model

Sludge is often considered as a non-Newtonian fluid, and its rheological behaviour can be described by the Bingham model (Eq. (1)), the Ostwald model (Eq. (2)), the Herschel-Bulkley model (Eq. (3)), and the Sisko model (Eq. (4)) (Guibaud et al., 2004; Hasar et al., 2004; Mori et al., 2006; Laera et al., 2007).

\[
\tau = \tau_0 + k \frac{dv}{dx}
\]  
Eq. (1)

\[
\tau = k \left( \frac{dv}{dx} \right)^n
\]  
Eq. (2)

\[
\tau = \tau_0 + k \left( \frac{dv}{dx} \right)^n
\]  
Eq. (3)

\[
\tau = \mu_B \frac{dv}{dx} + k \left( \frac{dv}{dx} \right)^n
\]  
Eq. (4)

where, \( \tau \) (Pa) is the shear stress, \( dv/dx \) (s⁻¹) is the shear rate. The consistency index \( k \) represents the cohesiveness of the fluid, and flow behaviour index \( n \) far from one means high deviation from Newtonian behaviour (\( n = 1 \) for Newtonian fluids) and the yield stress \( \tau_0 \) indicates the resistance of the sludge to the deformation until sufficient stress is applied to exceed the yield strength of the solid phase. The parameter \( \mu_B \) is the high shear limiting viscosity when the shear rate imposed on the fluid tends to an infinite value.

The ratio between shear stress and shear rate is defined as apparent viscosity (\( \mu_a \)):

\[
\mu_a = \frac{\tau}{\left( \frac{dv}{dx} \right)^n}
\]  
Eq. (5)

The parameter values of \( n, k, \tau_0 \) and \( \mu_B \) of the four models could be obtained by fitting the experimental data of various shear rates under a series of MLSS concentration (for Bingham and Ostwald models) or by adopting non-linear optimization algorithm (for Herschel-Bulkley and Sisko models). The parameters could be correlated to MLSS concentration through linear or exponential-power laws. Then, the four models mentioned above could be described as a function of the shear rate and variable MLSS.
and used to assess their simulations by fitting experimental data.

1.3 Analytical methods

Chemical oxygen demand (COD), MLSS and mixed liquor volatile suspended solids (MLVSS) were measured according to standard methods of Chinese NEPA (1997). CFV was determined using Cup-type Current Meter (LS45A, Chongqing Hydrological Instrument Inc., China). Sludge apparent viscosity was measured by a revolving viscosity meter (NDJ, TJ Environmental Facility Inc., Shanghai, China) under various shear rates. All above mentioned analyses were conducted in duplicates, and average values were reported.

The relations of sludge concentration and viscosity with membrane fouling in the MSTD process were studied according to the method described in our previous studies (Wang et al., 2006; Wu et al., 2007). Statistical analysis, including Pearson and Spearman’s rank correlations, was carried out using the software SPSS Incorporation (USA) to characterize the effects of MLSS concentration, viscosity on membrane fouling. Correlations are considered statistically significant at a 95% confidence interval ($P < 0.05$).

2 Results and discussion

2.1 Mathematical simulation of sludge concentration and destruction process

2.1.1 Mass balance analysis

The flow diagram together with the nomenclature used in the following mass-balance equations are shown in Fig. 2. In the MSTD process, the sludge concentration in reactor is mainly dependent on three factors: the thickening effects of membrane separation which enables the effluent free of SS; the biomass growth consuming soluble substrate of influent mixed liquor; and the digestion effects caused by endogenous decay. According to the principle, accumulation = inflow − outflow + generation, a mass balance equation for active biomass within the system boundary can be established as Eq. (6):

$$\frac{dX_a}{dt} = QX_{a,i} - QX_{a,d} + YQ(S_o - S_e) - K_d VX_a$$  \hspace{1cm} (6)

where, $dX_a/dt$ (g/(L-d)) is the rate of active biomass change in reactor; $V$ (L) is MSTD reactor volume; $Q$ (L/d) is influent flowrate, $X_{a,i}$ (g/L) and $X_{a,d}$ (g/L) are influent and effluent active biomass concentration, respectively; $S_o$ (g/L), and $S_e$ (g/L) are influent and effluent soluble substrate concentration measured as soluble COD (SCOD) of sludge supernatant, respectively; $K_d$ (d$^{-1}$) is endogenous decay coefficient; $Y$ (g VSS/g COD) is biomass yield coefficient, and $X_a$ (g/L) is active biomass concentration in the reactor.

The mass balance equation for non-biodegradable volatile suspended solids (nbVSS) in the system could be similarly developed and expressed by Eq. (7):

$$\frac{dX_n}{dt} = QX_{n,i} - QX_{n,e} + f_d K_d VX_a$$ \hspace{1cm} (7)

where, $dX_n/dt$ (g/(L-d)) is the rate of nbVSS change in reactor; $X_{n,i}$ (g/L) and $X_{n,e}$ (g/L) are influent and effluent nbVSS concentration, respectively; $f_d$ is fraction of biomass that remains as cell debris.

Another mass balance equation of inert inorganic suspended solids in the system can also be developed as shown in Eq. (8):

$$\frac{dX_i}{dt} = QX_{i,n} - QX_{i,o} + YQ(S_o - S_e)$$ \hspace{1cm} (8)

where, $X_i$ (g/L) is the inert inorganic suspended solids; $X_{i,n}$ (g/L) and $X_{i,o}$ (g/L) are influent and effluent inert inorganic suspended solids, respectively.

The models for evaluating the variations of MLVSS and MLSS in the reactor could be expressed as Eqs. (9) and (10), respectively.

$$VX_{\text{i,V}} = VX_{\text{o,V}} + t\left(\frac{dX_o}{dt} + \frac{dX_n}{dt}\right)$$ \hspace{1cm} (9)

$$VX_i = VX_o + t\left(\frac{dX_o}{dt} + \frac{dX_n}{dt} + \frac{dX_i}{dt}\right)$$ \hspace{1cm} (10)

where, $X_{i,V}$ (g/L) is the MLVSS concentration in the reactor at time $t$ (d), $X_{o,V}$ (g/L) is the influent MLVSS concentration, $X_i$ (g/L) is the MLSS concentration in the reactor at time $t$, and $X_o$ (g/L) is the influent MLSS concentration.

According to the fact that total MLVSS in the reactor equals the active biomass concentration $X_a$ plus the nbVSS concentration $X_n$, and the terms of $X_{a,n}$ and $X_{n,a}$ both equal 0 (membrane effluent is free of SS), substituting Eq. (6) and Eq. (7) into Eq. (9) produces the following Eq. (11) that can be used to evaluate the variations of the MLVSS concentration in the process.

$$X_{V_j} = \frac{X_{o,V} \left(1 + \frac{t}{\text{HRT}}\right) + \frac{Y}{\text{HRT}}(S_o - S_e)}{1 + \eta K_d (1 - f_d)}$$ \hspace{1cm} (11)

$$\eta = \frac{X_{a,d}}{X_{V_j}}$$

Similar equation for modeling MLSS variations in system could be obtained by substituting Eqs. (6), (7) and (8)
into Eq. (10).

\[ X_t = \frac{X_0 \left(1 + \frac{t}{HRT}\right) + \frac{t}{HRT} Y (S_o - S_e)}{1 + \varphi t K_d (1 - f_d)} \]

\[ \varphi = \frac{X_{a,t}}{X_t} \] (12)

2.1.2 Modeling of sludge concentration variations

The experimental data of MLSS, MLVSS concentrations and modeling values in MSTD during three operational cycles (15 d of each) are illustrated in Fig. 3. It can be observed that model predictions fit very well with experimental data. The three cycles in this study had similar variation trends of MLSS and MLVSS concentration in the MSTD process. During one cycle of operation with HRT 1 d, MLSS concentration continuously increased from about 4 to 34 g/L and MLVSS increased from about 3 to over 22 g/L.

In order to further elucidate the relationship among sludge concentrations, HRT and operation time, Fig. 4 was plotted based on Eqs. (11) and (12). It can be seen from Fig. 4a that MLVSS concentration increased more rapidly under lower HRT as operation time increased. It is attributed to the fact that the thickening effects tend to dominate with the decrease of HRT. Similar trend of MLSS variation can also be observed in Fig. 4b. During the design of MSTD process, if two control parameters such as HRT and MLVSS or MLSS are chosen, the operation time for one cycle, i.e., SRT could be determined through Fig. 4. It will, to a great extent, facilitate the design and operation of the MSTD process. It is worth pointing out that another important variable for aerobic digestion design and operation is volatile solids reduction (destruction) which will be discussed in the following sections.

2.1.3 Sludge destruction

A major objective of aerobic digestion is to reduce the mass of the solids for disposal. This reduction is assumed to take place mainly with the biodegradable content of the WAS, while there maybe some destruction of the nonorganics as well (Metcalf & Eddy Inc., 2003). The MLVSS and MLSS reduction rate in the MSTD reactor could be calculated through Eqs. (13) and (14), respectively.

\[ E_{D_{\text{V},t}} = \frac{\sum_0^t Q_t X_{o,t,V} - VX_{t,V}}{\sum_0^t Q_t X_{o,t} - VX_t} \]

\[ E_{D,t} = \frac{\sum_0^t Q_t X_{o,t} - VX_t}{\sum_0^t Q_t X_{o,t}} \] (13)

where, \( E_{D_{\text{V},t}} \) and \( E_{D,t} \) are the MLVSS and MLSS reduction rates at time \( t \), respectively, and \( Q_t \) (L/d) is the influent sludge flow at time \( t \).

Figure 5 shows the experimental data of MLVSS, MLSS destruction rate and the model simulation values based on Eqs. (13) and (14), demonstrating that the experimental data are roughly in agreement with the model predicted values. It could also be found that after 15 d operation about 42% of MLVSS and 39% of MLSS reduction could be achieved, and this could meet vector attraction requirements of 40 CFR Part 503 for sewage sludge treatment, i.e., a minimum of 38% reduction in volatile solids during biosolids treatment (USEPA, 1992).

Solids destruction is primarily a direct function of both liquid temperatures in the reactor and SRT. Figure 6 shows...
volatile solids reduction of this MSTD and conventional aerobic digesters reported by Water Environmental Federation (WEF, 1995) under various degree-days (temperature times SRT). It can be observed that the two digestion processes have similar variation trends as the degree-days increased, i.e., initially, the rate of volatile solids reduction increased rapidly as the degree-days increased while the curve begins to flatten as the degree-days approach a certain value for the two aerobic digestion processes. It can also be seen from Fig. 6 that the sludge reduction efficiency of MSTD process is higher than that of conventional aerobic digestion process for WAS treatment under same degree-days. In order to meet the vector attraction requirements of a minimum of 38% reduction in volatile solids, the MSTD process needs about 240 degree-days while conventional aerobic digester demands over 400 degree-days. The higher digestion efficiency achieved in the MSTD process could be attributed to the fact that in this process the influent undigested sludge under low concentration was continuously fed into the reactor and the influent undigested sludge would be blended with the previously digested sludge existing in the reactor to continue the digestion process. In fact, it has been proven that the destruction efficiency of MLSS and MLVSS in aerobic digestion can be enhanced by adding digested sludge into the digester filled with undigested WAS and the digested sludge could serve as the source of viable cell mass needed for the degradation of organic solids (Khalili et al., 2000; Wang et al., 2008). The MSTD process could naturally utilize the mechanisms and thus the digestion efficiency was higher compared to the conventional aerobic digestion process.

The correlations of MLVSS or MLSS destruction rate with obtained MLVSS or MLSS and HRT in MSTD process are plotted in Fig. 7. The solids destruction rate tended to increase with increasing HRT. The increase of operation time (i.e., SRT) could also result in the enhancement of solids reduction rate and increase the thickened sludge concentration at the end of each cycle. If MLVSS destruction rate is chosen, the required HRT and solids concentration of the MSTD process can be obtained according to Fig. 7, which could facilitate the design and operation of the process.

2.2 Sludge rheology properties

2.2.1 Rheological models to assess the variations of viscosity

In this study, a set of MLSS samples with concentrations of 3.30, 6.59, 9.89, 13.18, 16.48, 19.78, 23.82, and 28.58 g/L obtained at various operational time were used to measure their apparent viscosity at (25 ± 1)°C under shear rates 850, 1000, and 1850 s⁻¹. The following Eqs. (13)–(16), were respectively deduced from the Bingham model, Ostwald model, Herschel-Bulkley model and Sisko model, respectively, by using the apparent viscosity values under...
Various shear rates and MLSS concentrations. They could be used to predict the apparent viscosity of mixed liquor under different MLSS concentrations.

\[
\mu_a = 3249.1 \exp(0.0146\text{MLSS}) - (0.0058\text{MLSS} - 0.0737) \quad (15)
\]

\[
\mu_a = 1433.5 \exp(-0.0554\text{MLSS}) \times (0.1557 \exp(0.0428\text{MLSS}) - 1) \quad (16)
\]

\[
\mu_a = (15.953\text{MLSS} + 3121.7) \times (0.0101\text{MLSS}) \times (0.0247\text{MLSS} + 1.1366) \quad (17)
\]

\[
\mu_a = 0.1845 \exp(0.1010\text{MLSS}) + (115.57\text{MLSS} + 993.81) \times (0.0032\text{MLSS} - 0.8732) \quad (18)
\]

Figure 8 illustrates the plots of Eqs. (13)–(16) for three different shear rates versus MLSS concentrations. It can be observed in Fig. 8a that at shear rate 850 s\(^{-1}\) Herschel-Bulkley and Sisko models provided better estimations of apparent viscosity under different MLSS concentrations than other two models. Under shear rate 1000 s\(^{-1}\) (Fig. 8b), except for the Ostwald model, the rest models showed good simulations of measured viscosity value. However, under shear rate 1850 s\(^{-1}\) (Fig. 8c), Bingham and Sisko models demonstrated better estimation results than the other two models. It was also found that under shear rate 1850 s\(^{-1}\) the Herschel-Bulkley model showed good agreement with the experimental data under sludge concentration range 3.3–23.8 g/L, while it deviated the apparent viscosity of sludge concentration 28.6 g/L.

A fluid shows shear-thinning behaviour when its apparent viscosity decreases as the shear rate increases. A number of studies dealing with the rheological characterization of concentrated suspensions have been found to use shear-thinning models, i.e., Ostwald and Sisko models to simulate rheology behaviour (Lolito et al., 1997; Moeller and Torres, 1997; Seyssiecq et al., 2003; Laera et al., 2007). In this study, under shear rate range 850–1850 s\(^{-1}\), Sisko model showed better simulation results than Ostwald model for modeling the shear-thinning behaviour of thickened and digested WAS in MSTD process. It is also believed that a rigidity of the suspension structure should be overcome to induce flow due to the presence of sufficient suspensions (Ducla et al., 1983; Seyssiecq et al., 2003), and the concentrated suspensions are called as yield stress fluids which show viscoplastic behavior. Viscoplastic models such as Bingham and Herschel-Bulkley models could be employed to represent its rheological behavior (Dentel, 1997). From Fig. 8, it can be seen that under 850 s\(^{-1}\) Herschel-Bulkley model demonstrated good modeling effects while Bingham model obviously deviated experimental data; however, Bingham model could well simulate the apparent viscosity of various sludge concentrations under 1850 s\(^{-1}\). Under 1000 s\(^{-1}\), Herschel-Bulkley and Bingham models were both applicable for modeling their viscoplastic behavior. These results indicated that under different shear rates the fluids could show different rheological behaviors, therefore, appropriate models should be developed to simulate and characterize their flow behavior.

2.2.2 Relationship between sludge concentration, viscosity and membrane fouling

The effects of sludge concentration in terms of MLSS and apparent viscosity on membrane fouling were studied in this MSTD process. The method reported in publications (Wang et al., 2006; Wu et al., 2007) was adopted to determine the membrane fouling rate. Table 1 lists the statistical analysis results of the correlations of MLSS concentration, apparent viscosity and membrane fouling rate in the MSTD process. It was found that MLSS concentration had significant correlations with membrane fouling and their Pearson’s correlation coefficient \(r_p = 0.909\) (\(P < 0.01\)). Apparent viscosity also had positive correlations with membrane fouling with \(r_p = 0.949\) (\(P < 0.01\)). The results showed that MLSS and viscosity were two important parameters affecting the performance and operation process of MSTD process. This result is generally in accordance with previous studies which reported that

<p>| Table 1 Pearson’s correlation coefficient ((r_p)) of MLSS concentration, viscosity and fouling rate |
|-----------------------------------------------|------------------|------------------|------------------|</p>
<table>
<thead>
<tr>
<th>MLSS</th>
<th>Viscosity</th>
<th>Membrane fouling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.920**</td>
<td>0.909**</td>
</tr>
<tr>
<td>0.920**</td>
<td>1</td>
<td>0.949**</td>
</tr>
</tbody>
</table>

** Correlation is significant at 0.01 level (2-tailed).
viscosity and MLSS concentration could affect membrane fouling and membrane permeability during membrane filtration (Rosenberger et al., 2002; Meng et al., 2007; Wu et al., 2009). During the design and operation process of MSTD, MLSS and viscosity should be taken into account to control membrane fouling and to maintain the membrane permeability. A higher thickened and digested MLSS concentration would be beneficial to the disposal of WAS; however, it might be detrimental to membrane filtration of MSTD. Therefore, an operationally acceptable MLSS concentration to be obtained at the end of one cycle in MSTD process is worth further investigating. Besides, related membrane fouling control strategies also need attention, e.g., the addition of some coagulant to the reactor.

3 Conclusions

Sludge concentration variations and rheology properties in MSTD process for WAS treatment were critically studied in present study, and the following conclusions could be drawn.

(1) WAS could be thickened from about 4 to 34 g/L under HRT 1 d and SRT 15 d in MSTD process, and MLVSS reduction rate could reach 42%. Based on mass balance analysis, mathematical models were developed and could be used to predict and evaluate the variations of sludge concentration and the digestion efficiency in the MSTD process.

(2) The sludge in MSTD process showed both shear-thinning and viscoplastic behaviour, and under various shear rates different rheological models could be chosen to characterize their flow behaviour.

(3) Sludge concentration and viscosity were found to be two important factors affecting membrane fouling and operation of MSTD process in this study.

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