A simple empirical model for the clarification-thickening process in wastewater treatment plants

Y. K. Zhang, H. C. Wang, L. Qi, G. H. Liu, Z. J. He and H. T. Fan

ABSTRACT

In wastewater treatment plants (WWTPs), activated sludge is thickened in secondary settling tanks and recycled into the biological reactor to maintain enough biomass for wastewater treatment. Accurately estimating the activated sludge concentration in the lower portion of the secondary clarifiers is of great importance for evaluating and controlling the sludge recycled ratio, ensuring smooth and efficient operation of the WWTP. By dividing the overall activated sludge-thickening curve into a hindered zone and a compression zone, an empirical model describing activated sludge thickening in the compression zone was obtained by empirical regression. This empirical model was developed through experiments conducted using sludge from five WWTPs, and validated by the measured data from a sixth WWTP, which fit the model well ($R^2 = 0.98$, $p < 0.001$). The model requires application of only one parameter, the sludge volume index (SVI), which is readily incorporated into routine analysis. By combining this model with the conservation of mass equation, an empirical model for compression settling was also developed. Finally, the effects of denitrification and addition of a polymer were also analysed because of their effect on sludge thickening, which can be useful for WWTP operation, e.g., improving wastewater treatment or the proper use of the polymer.

Key words | compression settling, model, sludge thickening, wastewater treatment plant

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NOMENCLATURE

X_s	sludge concentration at the bottom of the clarifier (g/L)
X_0	initial sludge blanket concentration (g/L)
X_∞	final sludge concentration at the end of thickening (g/L)
X_r	return sludge concentration (g/L)
X_{sb}	sludge blanket concentration (g/L)
X_c	sludge concentration when the compression-thickening commences (g/L)
t	sludge blanket retention time (h)
t'	hydraulic residence time (h)
t_c	time when compression settling commences (h)
t_s	duration of compression settling (h)
Δt	compression time advancement parameter (h)
H	sludge blanket height (m)
H_0	initial sludge blanket height (m)
Q_r	return sludge flow rate (m^3/h)
A	area of the floc
A'	surface area of clarifier (m^2)
a, b, c	parameters of the model in this study
d, f	parameters of Roche's model
m, n	parameters of Zhang's model
n'	number of clarifiers
v_{cs}	compression settling velocity (m/h)
u_{cs}	sludge-thickening velocity (g/h L)
SVI	sludge volume index (mL/g)
D_2	two-fractal dimension of the floc
D_3	three-fractal dimension of the floc
V	volume of the floc
P	perimeter of the floc

INTRODUCTION

Sludge thickening and clarification occur simultaneously in wastewater treatment plants (WWTPs). Determination of

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the activated sludge concentration at the bottom of a secondary clarifier is necessary for proper design and operation of a WWTP. Thus, sludge thickening must be taken into account for evaluation.

Kynch (1952) developed the solids flux theory, which is often considered the origin of modern sedimentation and sludge-thickening research. This approach is simple but not very realistic, as it does not consider the biological effects and sludge settleability. Moreover, activated sludge can rapidly reach a compression phase in a secondary settling tank, violating the assumptions of the solids flux theory. Subsequently, Hultman & Hultgren (1980) described deviations from the Kynch theory, developing a modified consolidation theory to describe the thickening process of activated sludge, which included permeability, K, and a compression module, M, as properties of the sludge. However, these two parameters are very difficult to measure because of the high precision required. Roche et al. (1995) presented a semi-empirical equation for prediction of the return activated sludge concentration under non-steady-state conditions. The model is described by the following general equation:

$$X_s = d(t' + \Delta t)^f \quad (1)$$

$$\Delta t = 0.086X_0^{2.234} \quad (1a)$$

$$d = 2.056X_0^{0.382} \quad (1b)$$

$$f = 0.545\mathrm{SVI}^{-0.152} \quad (1c)$$

where X_s is the sludge concentration at the bottom of the clarifier (g/L), t' is the hydraulic residence time (h), Δt is the compression time advancement parameter (h), and d and f are empirical parameters. Pipes et al. (1996) suggested that the actual time during which the activated sludge stays in the clarifier is determined by the following equation:

$$t = (A')(H)(X_{\mathrm{sb}})/(n'Q_rX_r) \quad (2)$$

where t is the sludge blanket retention time (h), A' is the surface area of the clarifier (m^2), n' is the number of clarifiers, X_{sb} is the sludge blanket concentration (g/L), X_r is return sludge concentration (g/L), and Q_r is the return sludge flow rate (m^3/h). Moreover, they suggested that Δt can be neglected, because its value is negligible. Considering the discussion of Pipes et al. (1996) and combining Equations (1) and (2), the initial model can be rearranged as follows:

$$X_r = \left\{d[(A')(H)(X_{\mathrm{sb}})/n'Q_r]^f\right\}^{1/(f+1)} \quad (3)$$

Equations (1) and (3) are too complex to be widely applied and cannot predict X_r accurately.

Several factors, such as thickening time, sludge-thickening properties, temperature, turbulence, denitrification and polymers, can affect sludge thickening. However, temperature, turbulence, denitrification and polymers affect sludge thickening primarily by changing the sludge volume index (SVI), which is the sludge-thickening property. Therefore, sludge thickening should be closely related to thickening time and SVI. In this study, we aimed to propose a simple empirical model that can predict X_r simply and accurately by means of a regression for activated sludge thickening using easily measurable parameters, such as the sludge blanket retention time t in the secondary settling tanks and the sludge-thickening property, SVI, rather than a mathematical model that requires substantial computational effort and careful estimation of a variety of parameters.

MATERIALS AND METHODS

Sampling

Activated sludge was collected from six different WWTPs in Beijing, China, and the samples were used for experiments a maximum of 12 h after collection. Measurement of the activated sludge concentration at the bottom of the column was conducted using a Tengine® MLSS 10AC (Tengine, China).

Sludge-thickening experiment

A standard settling column (Figure 1(a)) with a height of 1.2 m and inner diameter of 200 mm, large enough to avoid wall effects, equipped with a column stirrer (1 rpm) driven by a speed controller engine was used for the batch settling tests. To minimise biochemical reactions during the thickening process, a thickening time of 2 h was selected. In the tests, the initial sludge concentration was set to X_c, as the sludge concentration was considered to have already reached X_c in the sludge blanket of the secondary settling tanks. The X_{sb}-time curves were obtained for WWTPs 1–6, as were the H-time curves, which exist in

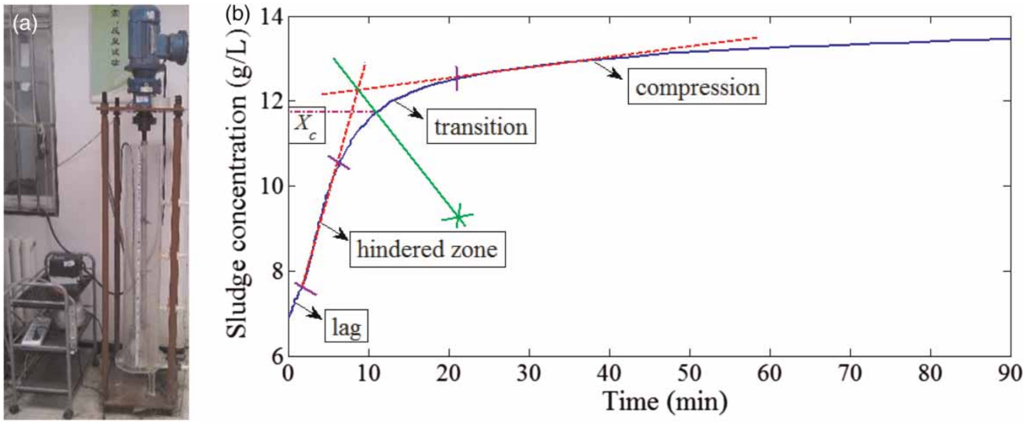

Figure 1 | (a) Schematic diagram of experimental set-up, and (b) example-thickening curve for the activated sludge.

four zones of the thickening process (the lag, hindered, transition and compression zones). To determine X_c, a graphical method was applied, using the intersection of the thickening curve and bisector of the angle formed by the tangents to the hindered zone and compression zone areas of the curve (Figure 1(b)); this was considered the approximate critical point at which compression commences.

RESULTS AND DISCUSSION

Model development

The experimental data for the six settling tests were divided into two groups. WWTPs 1–5 were used to establish the model, which was then validated using the data from WWTP 6. Therefore, five sludge-thickening curves in the compression zone were used to determine the model parameters (Figure 2).

From Figure 2, it can be seen that the sludge-thickening process was well correlated with SVI values. Based on the curve profiles, the following exponential function was selected to describe the sludge-thickening process:

$$X_s = ae^{b/t} + c \quad (4)$$

where t is the sludge blanket retention time (h), X_s is the sludge concentration at the bottom of the clarifier (g/L), and a, b, and c are empirical parameters, with $b < 0$. The results of regression analysis applying Equation (4) to the experimental data showed a good fit for all data, with all of the coefficients of determination (R^2) close to 0.99, suggesting that the exponential function of Equation (4) was suitable for modelling the thickening process in WWTPs 1–5 used in this study. These results also show that different activated sludges have similar thickening behaviour. SVI, X_c, R^2, a, b and c for all experiments are shown in Table 1. Additionally, F-tests for the five models in Table 1 showed that the null hypotheses were significant ($p < 0.001$), and t-test in each model also showed a high level of significance ($p < 0.001$), indicating that the five models showed strong correlations between X_s and SVI. The assumptions of normal and independent distributions of residuals in the models were verified ($p = 0.051$), indicating that the model had low variance.

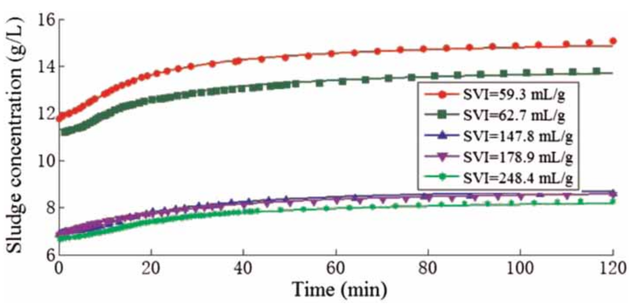

Figure 2 | Five sludge-thickening curves in the compression zone.

Table 1 | SVI, X_c, R^2, and the parameters a, b and c obtained for all experiments

WWTP	SVI (mL/g)	X_c (g/L)	a	b	c	R^2	p
1	59.3	11.78	3.19	–14.5	12.00	0.99	<0.001
2	62.7	11.16	2.70	–15.4	11.31	0.99	<0.001
3	147.6	6.86	1.79	–17.4	6.95	0.99	<0.001
4	178.9	6.82	1.84	–18.2	6.99	0.98	<0.001
5	248.4	6.66	1.72	–19.4	6.72	0.99	<0.001

For a given WWTP, the parameters a, b and c are all constants. Therefore, the first derivative of X_s can be obtained through the following equation to calculate u_{cs}, the sludge-thickening velocity (g/h L):

$$u_{cs} = \frac{dX_s}{dt} = -abe^{\frac{b}{t}}/t^2 \quad (5)$$

where a and b are WWTP-specific constants and $b < 0$. This equation provides a new approach to assess the potential of the sludge thickening. Equation (5) demonstrates that u_{cs} decreases with an increase in t and, when t approaches infinity, u_{cs} approaches zero, consistent with the sludge-thickening process.

An empirical model for the compression settling

Few researchers have described the compression settling process clearly because the mechanism of compression settling is more complex than that of hindered settling. Härtel & Pöpel (1992) proposed a dynamic secondary clarifier model that included the process of sludge thickening, by modifying the Vesilind settling velocity function with Ω (a correction coefficient). Zhang *et al.* (2006) subsequently presented the following compression settling model:

$$v_{cs} = \frac{mn}{(t_s + t_c)^2} \times e^{n/(t+t_c)} \quad (6)$$

where v_{cs} is the compression settling velocity (m/h), t_c is the time at which compression settling commences (h), t_s is the duration of compression settling (h), and m and n are model parameters. However, this equation has too many parameters to be widely used in the design and control of WWTPs.

Assuming the sludge concentration in the compression settling zone is nearly homogeneous, Talmage & Fitch (1955) developed a function based on the conservation of mass equation:

$$H_0X_0 = HX_s \quad (7)$$

Combining Equations (4) and (7), the following equation can be obtained:

$$H = H_0X_0/\left(ae^{\frac{b}{t}} + c\right) \quad (8)$$

where $b < 0$. For a given WWTP, the parameters a, b, c, H_0 and X_0 are all constants. Therefore, the first derivative of Equation (8) can be used to determine the compression settling v_{cs}, as follows:

$$v_{cs} = -\frac{dH}{dt} = -\frac{H_0X_0abe^{\frac{b}{t}}}{t^2\left(ae^{\frac{b}{t}} + c\right)^2} \quad (9)$$

In Equation (9), v_{cs} decreases with increasing t and, when t approaches infinity, v_{cs} approaches zero, consistent with the process of sludge settling. Furthermore, the model is simpler to describe the sludge-settling velocity than previous models, as it incorporates the two important parameters SVI and t.

MODEL CALIBRATION

Determination of *a*, *b* and *c*

The parameters a, b and c were found to be well correlated with the SVI value (Table 1). Through regression analysis of a, b and c and the corresponding SVI values, Equations (10)–(12) were obtained as follows:

$$a = 15.593\text{SVI}^{-0.408}\left(R^2 = 0.92, p = 5.32 \times 10^{-4}\right) \quad (10)$$

$$b = -3.17\ln(\text{SVI}) - 1.869\left(R^2 = 0.97, p = 4.90 \times 10^{-6}\right) \quad (11)$$

$$c = 66.023\text{SVI}^{-0.428}\left(R^2 = 0.94, p = 1.92 \times 10^{-4}\right) \quad (12)$$

Combining Equations (4) and (9) with Equations (10)–(12), we obtain

$$X_s = 15.593\text{SVI}^{-0.408}e^{[-3.171\ln(\text{SVI}) - 1.869]/t} + 66.023\text{SVI}^{-0.428} \quad (13)$$

$$v_{cs} = \frac{15.593\text{SVI}^{-0.408}[3.17\ln(\text{SVI}) + 1.869]H_0X_0}{t^2\left(15.593\text{SVI}^{-0.408}e^{\frac{[-3.17\ln(\text{SVI}) - 1.869]}{t}} + 66.023\text{SVI}^{-0.428}\right)^2} \quad (14)$$

where 59.3 mL/g $\leq$SVI$\leq$ 48.4 mL/g, $t > 0$ h and 6.23 g/L $< X_s <$ 3.99 g/L. If the SVI value for a WWTP is available, X_s and v_{cs} can be easily obtained in WWTPs tested in this study without the need for additional complex experiments or computational efforts. However, they should be tested first to confirm the applicability of this approach on a broader scale.

Model validation

The model was verified using the data from WWTP 6 obtained in the laboratory. The SVI value was 209.8 mL/g and X_r was 6.5–7.3 g/L. The parameters $a = 1.76$, $b = -18.8$ and $c = 6.88$ were obtained using Equations (10)–(12). Therefore, the thickening function for WWTP 6 was

$$X_s = 17.6e^{-18.8/t} + 6.88 \quad (15)$$

The measured data had a good fit with Equation (15) with a coefficient of determination of $R^2 = 0.98$, but did not fit Equation (1) or (3) (Figure 3). Therefore, the current model predicted X_r well, while Equation (1) gave an incorrect result.

Factors affecting sludge thickening

Factors such as denitrification and polymer conditioning were analysed because of their effect on sludge thickening, which can be useful for WWTP operation.

Denitrification

Denitrification, in which nitrites and nitrates are converted into nitrogen gas and released into the air, is one of the most common processes in a secondary settling tank. Sludge thickening decreases with nitrogen gas generation and accumulation. If enough gas is formed, the sludge mass becomes buoyant and rises or floats to the surface, substantially decreasing the whole clarification efficiency (Swayne et al. 2010).

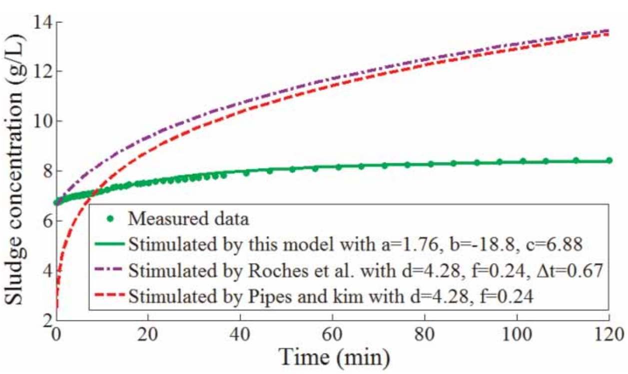

Figure 3 | Sludge concentration as a function of SVI.

To evaluate this process, the activated sludge from WWTP 5 was divided into two fractions. One fraction was used to do the initial experiment, and the other fraction was stirred slowly at 6 rpm for 12 h before the experiment to allow the generated gas to escape from the sludge and minimise the effects of denitrification (Figure 4).

Denitrification was found to decrease the sludge thickening heavily. The final sludge concentration at the end of thickening X_∞ increased by 15.6%, from 8.28 g/L with denitrification to 9.57 g/L without denitrification (Figure 4). These results demonstrate that improving the wastewater contributes to the activated sludge thickening.

Polymer conditioning

The effect of polymer conditioning on the thickening behaviour of activated sludge in a secondary settling tank was analysed. Cationic polyacrylamide (PAM) dosages of 0–9 ppm were tested to evaluate the relationship between polymer flocculation and sludge-thickening behaviour. The activated sludge used in this experiment was collected from WWTP 4 (SVI = 178.9 mL/g); the results are shown in Figure 5(a).

In Figure 5(a), smaller doses of cationic PAM improved sludge thickening, but above that level, overdosing occurred and the sludge was increasingly more difficult to thicken, indicating that formation of a networked sludge structure plays a controlling role in thickening behaviour.

Sludge flocs are highly porous fractal-like aggregates of many primary particles. In recent years, irregular aggregate shapes have been described in terms of fractal geometry concepts (Jin & Wand 2001; Perez et al. 2006; Wang & Dentel 2010) through the following equations:

$$A \propto P^{D_2} \quad (16)$$

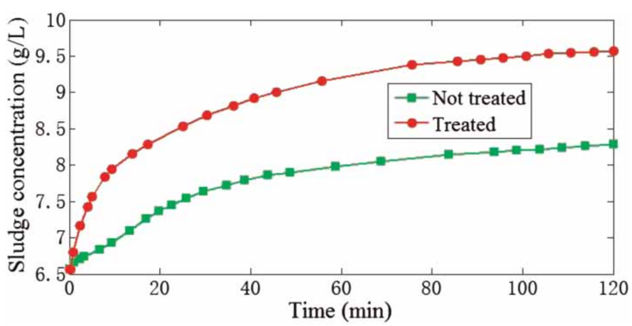

Figure 4 | Effect of denitrification on sludge thickening ('treated' refers to the experiment without denitrification, and 'not treated' refers to the experiment with denitrification).

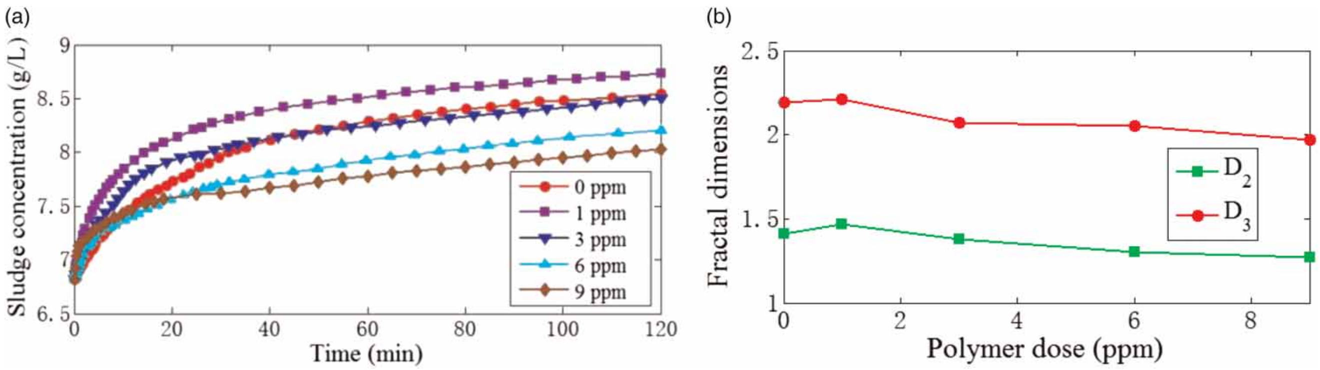

Figure 5 | (a) Activated sludge thickening, and (b) D_2 and D_3 for sludge flocs with different cationic PAM doses (D_2 and D_3 refer to the two- and three-fractal dimensions of the floc, respectively).

$$V \propto P^{D_3} \quad (17)$$

where A is the area of the floc, V is the volume of the floc, P is the perimeter of the floc, and D_2 and D_3 are the two- and three-fractal dimensions of the floc, respectively. Higher D_2 and D_3 indicate more compact sludge flocs. We determined D_2 and D_3 of the sludge flocs after adding various polymer dosages using an Image-Pro Plus 6.0 (Media Cybernetics, USA).

D_2 and D_3 for the sludge flocs achieved a maximum of 1.47 and 2.21, respectively, with 1 ppm cationic PAM (Figure 5(b)). As the dose increased, D_2 and D_3 decreased from 1.47 to 1.26 and from 2.21 to 1.97, respectively, in good agreement with the trends in sludge thickening (Figure 5(a)). The results showed that the more compact sludge flocs had better thickening performance.

CONCLUSIONS

A new model, $X_s = 15.593\,\mathrm{SVI}^{-0.408}\ e^{[-3.171\ln(\mathrm{SVI})-1.869]/t} + 66.023\mathrm{SVI}^{-0.428}$, describing activated sludge thickening during compression was developed that has a large advantage over previous models because only one parameter, SVI, needs to be applied. WWTP operators can use the SVI values to determine the model parameters for their WWTP and modify the sludge blanket retention time t in the secondary settling tanks to obtain the desired X_r. Thus they can evaluate and control the sludge recycling ratio, ensuring efficient and smooth WWTP operation.

An equation for the sludge-thickening velocity, $u_{cs} = -abe^{b/t}/t^2$, $(b < 0)$, was obtained from the first derivative of the new model, which provides a new way to assess the potential of the sludge-thickening process. Combining this new model and the conservation of mass equation ($H_0X_0 = HX_s$), a new model for compression settling $v_{cs} = -H_0X_0abe^{b/t}/t^2\left(ae^{\frac{b}{t}} + c\right)^2$, $(b < 0)$, was also established, which more accurately describes the sludge-settling velocity than previous models, as it incorporates the two important parameters SVI and t.

Additionally, based on our results, denitrification has an obvious inhibition for sludge thickening. Therefore, improving wastewater treatment can also contribute to the activated sludge thickening.

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