UV DISINFECTION OF CHEMICALLY ENHANCED PRIMARY EFFLUENT: MODELING UV TRANSMITTANCE INFLUENCING PARAMETERS

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Abstract

The advancement of UV technology has pushed the applications of UV disinfection to treat primary effluents recently. Installation of UV disinfection after chemically enhanced primary treatment (CEPT) has been implemented in Hong Kong since 2007. However, there are many factors that affect the UV transmittance (UVT) of CEPT effluents such as the effluent quality, CEPT operating parameters and characteristics of wastewater. This research gave the first attempt in developing mathematical expression of this complicated system. A nonlinear regression model was proposed to evaluate the UVT of CEPT effluents with various parameters under different operational conditions. UVT values were found to correlate with total suspended solids (TSS), dissolved organic carbon (DOC), and dissolved iron concentrations. The model simulation and sensitivity analysis results suggested that reducing TSS concentrations could be an effective means to enhance UVT values. Results on evaluation of the changes in operational parameters to reduce TSS suggested that UVT could be improved by enhancing the rapid mixing, extending the slow mixing time, and increasing ferric chloride doses. The operational conditions and influent wastewater qualities were combined in one model to predict UVT in the CEPT effluent.

Keywords: CEPT, UV transmittance, Model, Influencing factors, Operating parameters, Wastewater quality

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INTRODUCTION

Chemically enhanced primary treatment (CEPT) involves the additional use of chemicals, metal salts and/or polymers, and the incorporation of coagulation and flocculation processes prior to the conventional primary treatment of wastewater to facilitate the settling of suspended solids from wastewater. Disinfection of the CEPT effluent is nevertheless necessary as CEPT can only achieve about 50% of total coliform reduction.[1] The quality of CEPT effluent is affected by operating parameters, such as coagulant/flocculent types and doses [2,3] and mixing strength and time [4,5].

UV disinfection is a viable alternative to chlorine disinfection and has little disinfection by-product (DBP) formation at common disinfection doses.[6]

In the design and operation of UV systems, it is well known that the performance of UV systems is influenced by water clarity, which is commonly described by a parameter termed as UV transmittance (UVT). UVT is practically defined as the percentage of light intensity that can pass through a 10 mm path length of the solution over the initial light intensity of the blank, measured by a spectrophotometer using a specified wavelength at 254 nm.[7] Typical UVT values of primary, secondary and tertiary effluents are in the ranges of 28-50%, 45-70%, and 80-98%, respectively.[7] Because of the high energy cost for treating primary effluents with low UVT, UV disinfection was chiefly applied to effluents with secondary or tertiary treatment.

In recent years, the advancement of UV technologies has pushed the applications of UV disinfection to treat low-UVT primary effluents. Installation of UV disinfection after CEPT has been implemented in Hong Kong since 2007.[8] The operating experience of UV disinfection suggests that the UVT of CEPT effluents can be affected by the effluent quality and CEPT operating parameters such as the effluent TSS concentrations, coagulant doses and types, mixing strength and time as aforementioned. It has also been reported in the literature that various constituents in water, such as particles, organic matters and inorganic compounds (e.g. iron), can lower UVT and further lead to lower disinfection efficiency.[9-12] However, as the quality of incoming wastewater can vary significantly with time and isolating each UVT influencing component is difficult or impossible, the predominance among different UVT influencing components remains unknown, hence complicating the formulation of UVT improvement strategies.

This research gave the first attempt in developing mathematical expression of this complicated system. We developed two mathematical models, based on Beer's Law, for describing UVT of CEPT effluents as functions of UVT-influencing water quality and CEPT operating parameters, respectively, with experimental data collected from jar test simulation using screened sewage collected at one sewage treatment works in Hong Kong. We also demonstrated the uses of the models to determine the relative importance of UVT-influencing parameters and to recommend operating strategies for enhancing CEPT effluent UVT, thus to improve disinfection performance and reduce energy cost.

MATERIALS AND METHODS

Solution preparation

All chemical solutions except described elsewhere were prepared from reagent grade chemicals or stock solutions. A stock solution of ferric chloride ($FeCl_3$, 50% by weight) and anionic polymer powder (AN 923 SH STONE HK) were obtained from a sewage treatment works employing CEPT as the main treatment scheme in Hong Kong.

Field sampling

The screened influent was collected from the same sewage treatment works on or one day before the testing day. Grab samples of the screened influent were collected and stored in 20-liter carboy containers for 14 sampling events covering different time periods including morning (around 10-11 am), afternoon (around 2-3 pm), and night (around 10-11 pm). The averages and relative standard deviations of water quality parameters, including UVT, TSS, pH, DOC and iron concentrations, of the influent are listed in Table 1, showing the variability of the influent samples.

Table 1 Characteristics of wastewater influent and effluent

	Influent		Effluent	
	Average	RSD (%)	Average	RSD (%)
UVT (%)	5	33	-	-
TSS (mg/L)	206	26	39	39
pH	7.2	3	7.2	2
DOC (mg/L)	36	67	32	48
Dissolved iron (mg/L)	0.10	34	0.18	55

Jar tests

Jar tests were performed to simulate the real operation at the sewage treatment works. The baseline and ideal conditions in conducting these jar tests are listed in Table 2. About 80 rounds of jar tests were performed.

Table 2 Operational conditions of the jar tests

	Baseline conditions	Ideal conditions
Rapid mixing speed (rpm)	32	130
Rapid mixing time (second)	53	30
Slow mixing speed (rpm)	33	33

Slow mixing time (min)	5	30
Polymer dose (mg/L)	0.1	0.1
Polymer addition time	1 min before settling	5 sec before slow mixing
Coagulant dose (mg/L)	10	10
Settling time (hour)	2	1.2

Only one CEPT operational parameter away from the current plant operational conditions performed for the jar tests or ideal conditions was changed at a time while others remained unchanged. The CEPT operational parameters changed included coagulant doses, polymer doses, slow mixing speeds, flocculation time and settling time.

Analytical methods

The collected supernatants, untreated screened influent, and effluent samples were subject to chemical analyses including pH, UVT, TSS, particle size distribution, and concentrations of residual coagulant and effluent organic matter (EfOM). The pH and TSS were measured according to the Standard Method [13]. EfOM was measured as DOC with a total organic carbon analyzer (Shimadzu TOC 5000A). The residual metallic ions in both soluble and particulate forms were measured according to the Standard Method [13] using an atomic absorption spectrometer (Hitachi Z-8200). UVT was measured with a UV-vis spectrophotometer (PerkinElmer Lambda25) at wavelength of 254 nm. The particle size distribution was obtained with a particle size analyzer (Coulter LS230).

Description of model simulation

The model is based on the Beer’s Law that the UV absorbance contributed from one single parameter is equal to its concentration multiplying with its specific UV absorbance, and the relationship between UVT and UV absorbance follows the following equation:

$$UVT = e^{\varepsilon_i \times [i]} \qquad \text{(Eq. 1)}$$

where ε_i and [i] are the specific UV absorbance at 254 nm and the concentration of component i, respectively. According to the Beer’s Law, it is also held true that the overall UV absorbance from two or more parameters is additive and thus the combining effect from two or more parameters on UVT shall be the multiple of the effects from these parameters. Thus, the mathematical model shall be established in this fashion and it involves multivariable nonlinear regression in the form of:

$$UVT = e^{\sum \varepsilon_i \times [i]} \qquad \text{(Eq. 2)}$$

To simply the model, components of relatively less importance, such as particulate iron, were rejected from the model simulation. TSS was fractionated into three fractions based on the size distribution: < 3 µm, > 10 µm, and in between. The fractionation is based on the particle size distribution curve, as shown in Figure 1, which displays a typical curve after coagulation. Two peaks with sizes less than 3 µm and about 10 µm were found. Therefore, components for model simulation consist of DOC, dissolved iron, and TSS (or fractionated TSS).

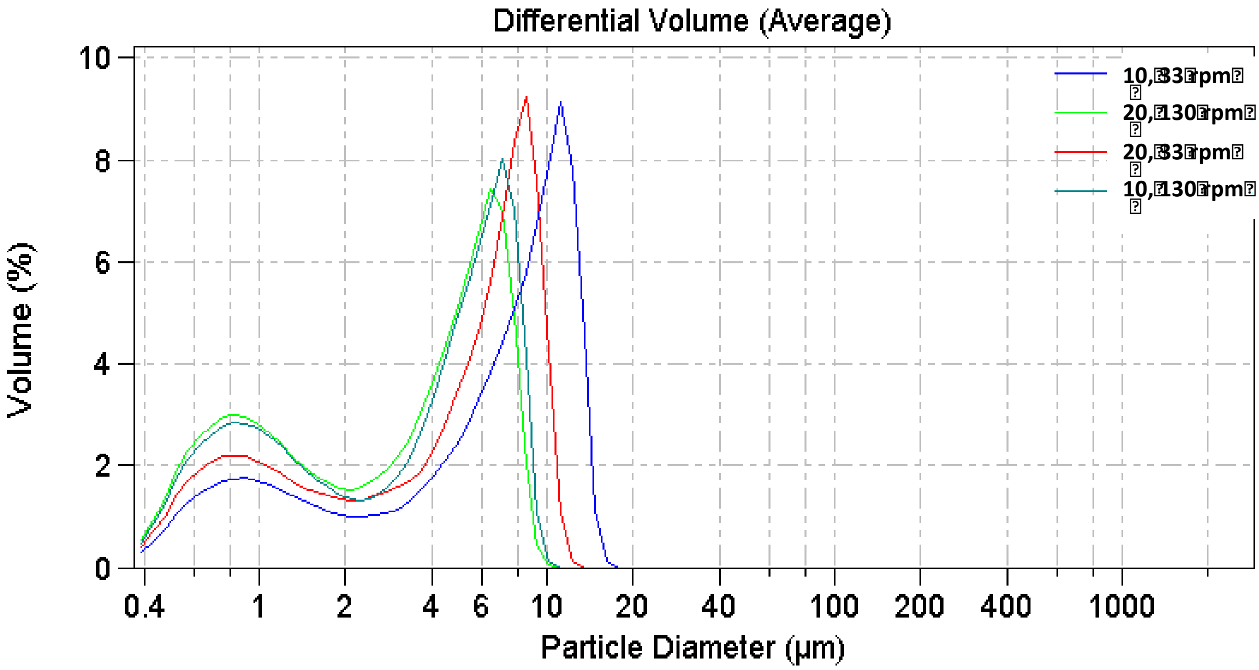


Figure 1 Particle size distribution curve after coagulation, at different rapid mixing speeds with ferric chloride doses (10 or 20 mg/L)

The criterion for evaluating the results of model simulation is the determination of coefficient, R^2, the value of which is between 0 and 1; the closer to 1 the R^2, the better the model fits.

RESULTS AND DISCUSSION

Model development

Over 40 simulations were performed. The figures presented in this section are with better fit and are selected for the ease of explanation. Figure 2(a) shows the correlation between measured and predicted UVT. A R^2 of 0.864 was obtained. The corresponding fit equation is:

$$UVT(\%) = e^{(-0.020\times[DOC]-0.032\times[TSS1]-0.021\times[TSS2]-0.029\times[TSS3]-0.005\times[dissolved\ iron])}\times 100\% \quad \text{(Eq. 3)}$$

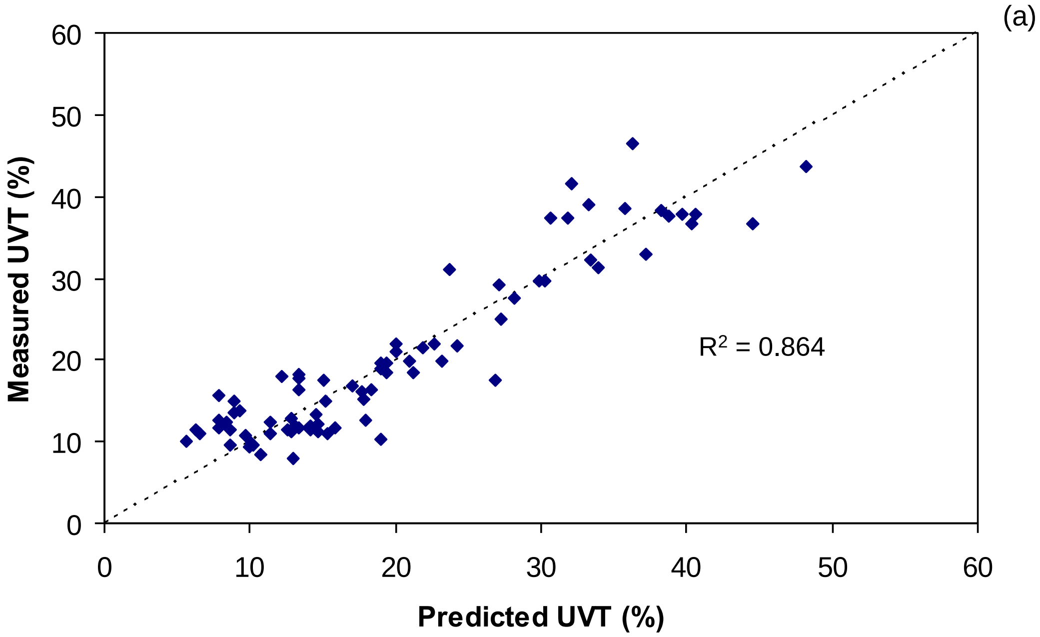
TSS fractionation: TSS1: < 3 µm; TSS2: ≥ 3 µm but < 10 µm; TSS3: ≥10 µm.

Figure 2(b) shows the correlation when overall TSS was used as one parameter. The corresponding fit equation is:

$$UVT(\%) = e^{(-0.016\times[DOC]-0.030\times[TSS]-0.538\times[dissolved\ iron])}\times 100\% \qquad \text{(Eq. 4)}$$

The R^2 value decreases slightly from 0.864 to 0.860 after the simplification but is yet deemed acceptable. The reason could be that particles larger than 10 μm constituted 60% or more of TSS generally and the fitted coefficients of the three TSS fractions did not vary much. Thus, the model treated with one single TSS term is chosen hereafter.

Comparing Eq. 3 and 4, the coefficient for dissolved iron obtained from data fitting changed from 0.005 to 0.538. Though the constants differ a lot in the two equations, the importance of the dissolved iron term remains small due to the very low concentrations of dissolved ion in the treated effluents. However, it should also be noted that including dissolved iron item in the simulation gives slightly better R^2 than excluding it, which suggests its contribution slightly to the UV absorbance.



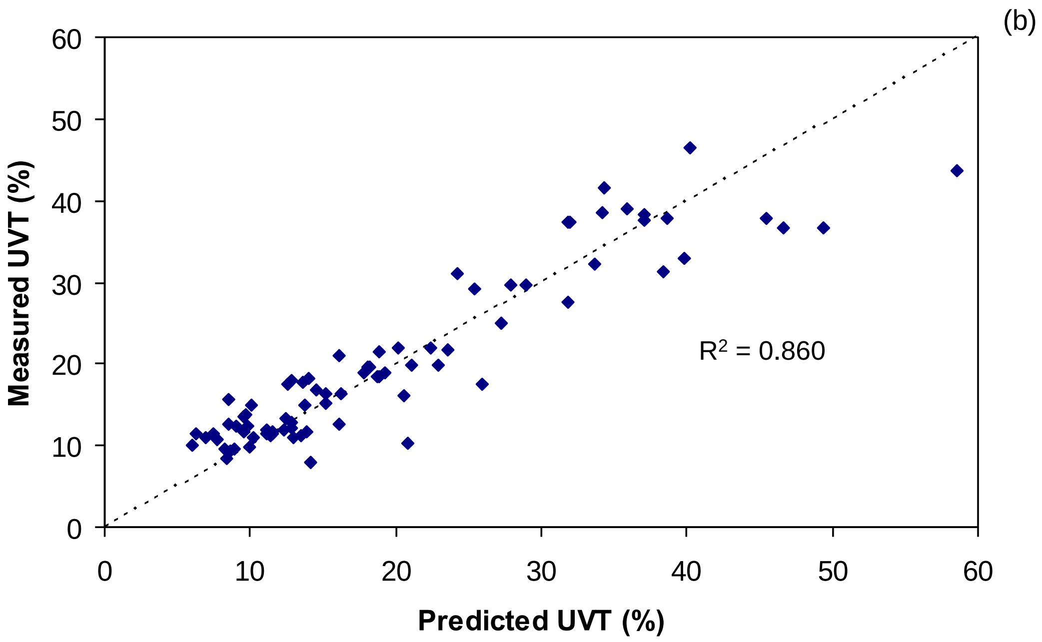


Figure 2 The predicted versus measured UVT from simulation with all data using ferric chloride as the coagulant and inclusion of (a) five components: three fractionated TSS, DOC, and dissolved iron; and (b) three components: TSS, DOC and dissolved iron.

Correlating TSS and UVT with operational parameters

Based on Eq. 4, the simulation results in Figure 3 show that coagulation did not remove DOC significantly and adding coagulant (ferric chloride) increased dissolved iron concentrations slightly. Data analyses indicate that reducing TSS concentrations is an effective means to enhance UVT values. Therefore, evaluation on the changes of operational parameters to reduce TSS was further investigated using jar test data, when jar tests were conducted with change of only one operational parameter at a time while other parameters were maintained under baseline conditions (see Table 2). To make data comparable with large variations in TSS concentrations produced under the same baseline operational conditions but in different test events (due to variability in influent water quality), normalization of the TSS concentration against the baseline TSS concentration in each testing event was performed, giving TSS percentage changes as a function of changes of each operational parameter shown in Figure 4.

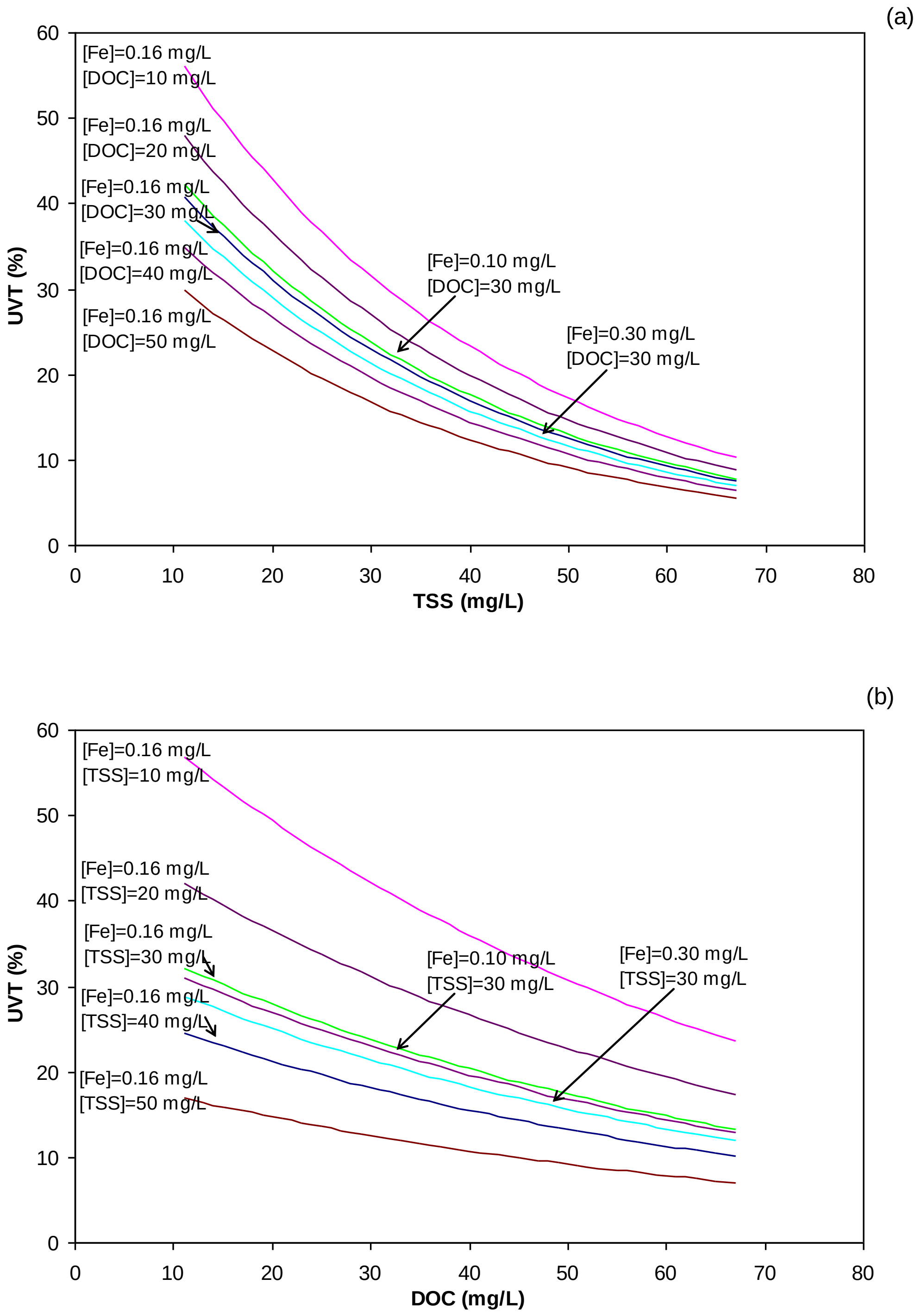


Figure 3 Changes in UVT as a function of changes of concentrations of TSS and DOC, respectively. (a) at given DOC and dissolved iron concentrations; (b) at given TSS and dissolved iron concentrations.

As shown in Figure 4, increasing polymer dose did not decrease TSS levels; on the contrary, increasing polymer dose from 0.1 mg/L to 0.14 mg/L increased TSS concentrations. Increasing setting time from 1.2 to 2 hours slightly reduced TSS concentrations; however, there was no clear trend of increase or decrease when the settling time was further increased from 2 to 2.8 hours. Slow mixing time seemed to affect TSS removal more. Increasing slow mixing time significantly reduced TSS concentrations. A 30-min slow mixing time reduced TSS concentrations by nearly 50%, compared to that obtained at a 5-min slow mixing time. Increasing slow mixing speed seemed to enhance TSS removal though one set of data were scattered. Increasing coagulant dose also reduced TSS values significantly. A rather linear trend of TSS concentrations as a function of ferric chloride doses was observed.

Rapid mixing speeds also affect TSS concentrations. A near-ideal rapid mixing speed (130 rpm) together with other near-ideal conditions (shown in Table 2) greatly reduced TSS concentrations. The near-ideal rapid mixing speed, together with ferric chloride doses of 20 mg/L in particular, produced supernatant of much lower TSS concentrations and higher UVT values. It was also found that, with the near-ideal rapid mixing, the dependency of UVT values to the slow mixing time became weaker.

In summary, there are clear trends showing significant improvement of UVT by providing near-ideal mixing, prolonging slow mixing time, and increasing ferric chloride doses to 20 mg/L. There are no clear trends of improving UVT by changing polymer doses and setting time from 2 to 2.8 hours.

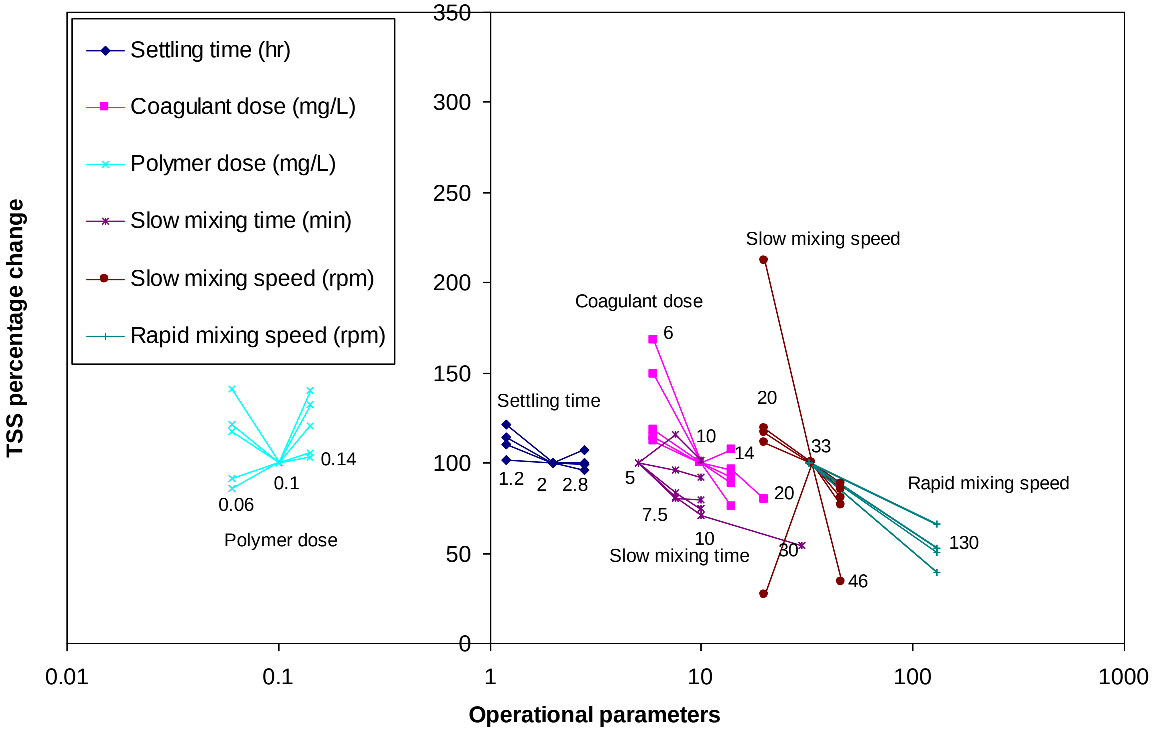


Figure 4 TSS percentage changes as functions of operational parameters including polymer dose, coagulant dose, settling time, slow mixing time and speed, and rapid mixing speed.

A model is trying to be developed to fit the values of TSS removal percentage and these operational parameters. The following relationship is found:

$$TSS\ removal(\%) = \left(1 - \frac{[TSS]_{eff}}{[TSS]_{inf}}\right) \times 100\% = (0.39 \times a + 0.33 \times b + 0.13 \times c + 0.039 \times d + 65.48) \times \frac{1}{100}$$

(Eq. 5)

a: coagulant dose; *b*: slow mixing time; *c*: slow mixing speed; *d*: rapid mixing speed.

Figure 5 shows the correlation between the measured and predicted TSS removal percentage based on Eq. 5. A R^2 of 0.685 is obtained.

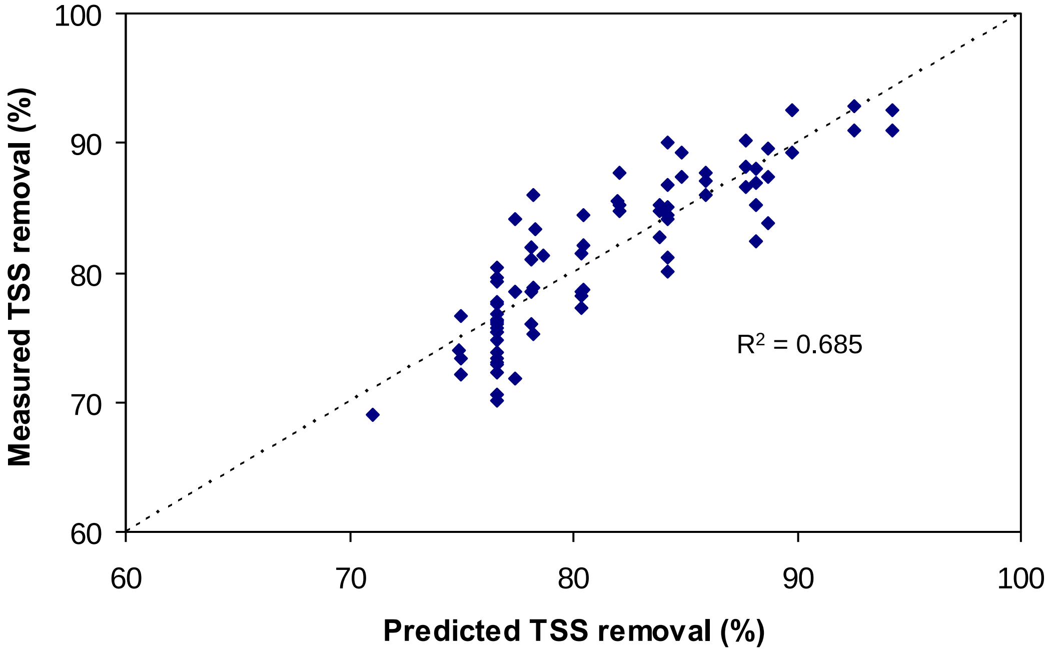


Figure 5 The predicted versus observed TSS removal percentage from simulation with all data and inclusion of four components: coagulant dose, rapid mixing speed, slow mixing speed and time.

Eq.5 can be incorporated to Eq. 4.

$$UVT(\%) = e^{(-0.016 \times [DOC]_{eff} - 0.030 \times [TSS]_{eff} - 0.538 \times [dissolved\ iron]_{eff})} \times 100\%$$

$$= e^{(-0.016 \times [DOC]_{eff} - 0.538 \times [dissolved\ iron]_{eff} - \frac{0.030}{100} \times [TSS]_{inf} \times (34.52 - 0.39 \times a - 0.33 \times b - 0.13 \times c - 0.039 \times d))} \times 100\%$$

(Eq. 6)

Predicted UVT based on Eq. 6 is correlated with measured UVT, as shown in Figure 6. A R^2 of 0.886

is obtained.

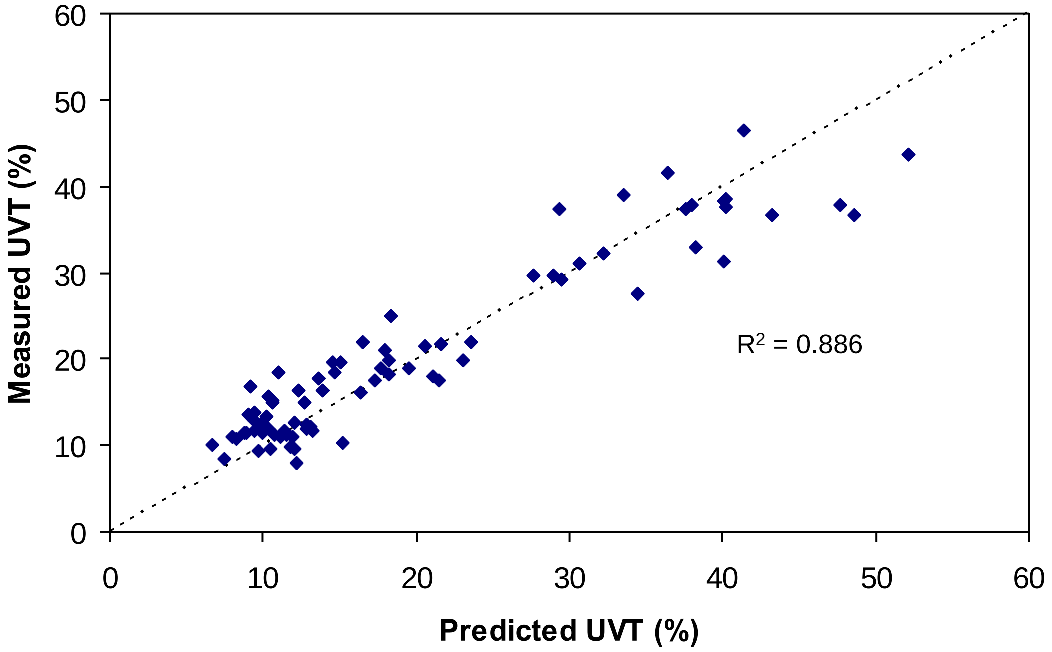


Figure 6 The predicted versus measured UVT from simulation with all data and inclusion of the following components: DOC, dissolved iron, TSS, coagulant dose, slow mixing speed and time, and rapid mixing speed.

From test results of this study, it is found that DOC concentrations do not change a lot in the treated wastewater, as shown in Table 1. Dissolved iron concentrations in the effluent will not affect UVT prediction significantly due to the small variation of its concentrations. For example, using minimum and maximum dissolved iron concentrations as shown in Figure 3, the difference of predicted UVT is only 4%, which is acceptable for model calculation. Therefore, both DOC and dissolved iron concentrations in the influent can be applied to Eq. 6 for application. Thus, Eq. 7 is derived here:

$$UVT(\%) \approx e^{\left(-0.016\times[DOC]_{inf}-0.538\times[dissolved\ iron]_{inf}-\frac{0.030}{100}\times[TSS]_{inf}\times(34.52-0.39\times a-0.33\times b-0.13\times c-0.039\times d)\right)}\times 100\% \qquad \text{(Eq. 7)}$$

Applications

Two equations were finally obtained from this study, Eq. 4 and 7, which related with wastewater effluent qualities and operational parameters, respectively. They could be applied for different purposes.

The predominant parameter affecting UVT could be obtained by conducting sensitivity analysis on Eq. 4. In each analysis, the concentrations of one component were allowed to change from the minimum to maximum occurring values obtained from the previous jar tests, while the concentrations of other components remained at given constants. Then changes in UVT as a function of changes of concentrations of all components were drawn. From the slope of the lines shown in Figure 3, changes of TSS concentrations affect UVT more than those of DOC. Therefore, reducing TSS levels will help to improve UVT values, which is consistent with the test results.

For a given wastewater and under a certain coagulation condition (characterized as *a*, *b*, *c* and *d*), UVT can be predicted by using Eq. 7. On the other hand, to achieve certain UVT values, operational parameters during coagulation can be proposed. For example, a wastewater with average concentrations in the influent (shown in Table 1: [TSS] = 206 mg/L, [DOC] = 36 mg/L, [dissolved iron] = 0.10 mg/L) is to be coagulated under the following conditions: coagulant dose of 10 mg/L, slow mixing time of 5 min, slow mixing speed of 33 rpm, and rapid mixing speed of 130 rpm. The predicted UVT for this treated wastewater is 16%. An increase of coagulant dose to 30 mg/L can give a UVT of 26%. A further increase of slow mixing time to 30 min can give a UVT of 43%.

In Eq. 7, three out of the four operational parameters were correlated with the mixing conditions during coagulation/flocculation. Combining with the jar test results, the low UVT in the effluent could be due to the sub-optimal mixing conditions during coagulation/flocculation process in the treatment plant. Therefore, efforts to enhance the contacts between coagulants and particles, such as providing better mixing and increasing slow mixing time, should improve the effluent quality. Changing polymer doses and increasing settling time do not improve UVT significantly probably because they do not contribute to better contacts between coagulants and particles.

The mathematical model developed from this study is applicable to the specific sewage treatment works investigated. The constants and parameters in the model may not be suitable for direct application in other plants. However, the concept and procedures to develop the model, as well as the evaluation of the relative importance of various parameters of wastewater qualities and operational conditions affecting effluent UVT can be applied to other treatment facilities. In addition, if a plant can develop a model as Eq. 7 from its own operational conditions, the effluent UVT could be predicted from any particular set of given influent wastewater qualities and operational conditions.

CONCLUSIONS

In the CEPT plant investigated, UVT values of the CEPT effluent have a nonlinear regression relationship with TSS, DOC, and dissolved iron concentrations. TSS affects UVT values mostly. UVT can be improved by increasing the coagulant dose, rapid mixing speed and slow mixing time. The operational conditions and influent wastewater qualities were applied in one model equation to predict UVT in the CEPT effluent.

The model generated from this study can be applied by the CEPT plant investigated to predict UVT of effluents and to evaluate operational strategies. This study also provides a simple means to evaluate the effects of different operational parameters on UVT. The concept and procedures could also be applied in other CEPT plants to improve UVT for more effective UV disinfection.

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