Improvement on algae and turbidity removal in an integrated flotation and sedimentation unit using side flow-inclined plate settlers: evidence from a full-scale field experiment

Ruijian Zhang, Zhimin Sun, Bin Cui, Pengfei Ren, Zhili Du, Xin Chai and Jing Lu

ABSTRACT

Operation of conventional drinking water treatment plants (DWTPs) is limited by seasonal variations in the characteristics of raw water, such as algae levels and turbidity. In this study, an integrated flotation and sedimentation unit (IFSU) with side flow-inclined plate settlers (SFIPS) was applied to enhance the removal ratio of algae and turbidity in a full-scale field experiment. To accomplish this, the performance of two IFSU reactors (with and without SFIPS) treating algal-rich water, low-turbidity water and high-turbidity water was compared. Extensive experiments were conducted based on a central composite face-centered design, and the results were analyzed using response surface methodology. Polyaluminium chloride dose, NaOH dose, influent turbidity level and influent chlorophyll level were selected as the operating variables to analyze, optimize and model the process. The results showed that SFIPS functioned as a counterflow inducer to enhance the effects of stratified flow patterns and decrease the clarification loading rate in the separation zone during the dissolved air flotation process, leading to considerable increases in algae and turbidity removal in the IFSU reactor. The results of this study will facilitate upgrades of conventional DWTPs to improve their potential.

Key words | drinking water treatment plants, DWTPs, full-scale field experiment, IFSU, integrated flotation and sedimentation unit, response surface methodology

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INTRODUCTION

Conventional drinking water treatment processes, including flocculation, dissolved air flotation (DAF), sedimentation, filtration and disinfection, target the removal of impurities such as turbidity, algae and organic matter, etc., from raw water (Hohner *et al.* 2016). As freak weather events and anthropogenic activity (including changes in landscape management, inputs of nitrogen and phosphorus amongst others), seasonal variations in the characteristics of raw water have presented more frequently in surface water, resulting in algal-rich water, low-turbidity water and high-turbidity water. These fluctuations can lead to a number of downstream problems such as algae or turbidity breakthrough, filter clogging (Buisine & Oemcke 2003), the presence of toxins (Al-Tebrineh *et al.* 2010) and the formation of harmful disinfection by-products (Chen *et al.* 2008). Thus, seasonal variations in the characteristics of raw water have become a great challenge for DWTPs.

When addressing the treatment of algal-rich water in DWTPs, ultrafiltration (UF) and flocculation-DAF have an edge over flocculation-sedimentation. But UF and

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flocculation-DAF would be ineffective when applied to high-turbidity water during rainy days (Henderson *et al.* 2010), while flocculation-sedimentation is reportedly more effective for the treatment of high-turbidity water (Li & Gregory 1991). Therefore, a novel water treatment system denoted IFSU (Li *et al.* 1993) was invented. The main advantage of the IFSU is that it can run flotation or sedimentation processes in a single unit. In these systems, flotation is induced when algal-rich or low-turbidity water is present, while sedimentation is induced when treating high-turbidity water. Since the invention of the IFSU in 1993 (Li *et al.* 1993), it has been successfully applied in the reservoirs of full-scale water treatment plants with volumes of up to 2 M l/d (Liu *et al.* 2012; Sun & Liu 2014).

In this study, we used a full-scale *in-situ* IFSU for the treatment of reservoir water. The main goal of the study was to compare the process performance of two IFSU reactors, with and without SFIPS. Response surface methodology (RSM) was employed to describe and model the variation trends of four significant responses for the treatment of algal-rich water, the removal efficiency of chlorophyll, turbidity, permanganate index (COD_{Mn}) and ammonia nitrogen (NH_4-N) as a function of three independent variables, polyaluminum chloride (PAC) dose, NaOH dose and influent chlorophyll (Chl_{in}) level. For the treatment of high or low-turbidity water, PAC dose, NaOH dose and influent turbidity (Tur_{in}) were selected as the variables, while the removal efficiency of turbidity, COD_{Mn} and NH_4-N were the responses. The results presented herein will facilitate upgrades of conventional DWTPs to enable the treatment of algal-rich, low-turbidity and high-turbidity water.

METHODS

IFSU reactor and operation

Our experiments were carried out over a few years in a full-scale IFSU plant in the Changkeng Reservoir (N22°24′26.45″, E113°23′48.86″; Zhongshan, Guangdong, China) that was used to generate drinking water. Based on the water quality between 2010 and 2013 (Table 1), the water in the system was made up of algal-rich water,

Table 1 | Main characteristics of the Changkeng Reservoir water

Parameters	Range	Unit
Chlorophyll	50–10,000	mg/l
Turbidity	3–300	NTU
COD_{Mn}	0.5–6	mg/l
Ammonia	0.05–0.6	mg/l

low-turbidity water and low-temperature or high-turbidity water on rainy days.

In this study, the 5 M l/d IFSU was divided into two portions, a SFIPS and a non-SFIPS IFSU system. The loading rate was 2.5 M l/d for both systems. Figure 1 shows the schematic diagram of the IFSU with SFIPS, and thumbnail (a) in this figure displays the exterior of the IFSU. The IFSU system consisted of a data monitor section, coagulation section, dissolved air canister (thumbnail (b)), dissolved air releaser (thumbnail (c)), SFIPS (thumbnail (d)) and a scraper and valve. A dissolved air canister maintained a saturator pressure of 0.35–0.40 MPa. The SFIPS inclined at an angle of 60° to the horizontal, and had a perpendicular spacing of 5 cm and a maximum length of 4 m.

Based on the flow process, raw water was first passed into the coagulation section. At this stage, PAC and NaOH were fed as the flocculant and assistant flocculant, respectively. Then, according to the algae and turbidity data acquired from the data monitoring section, the IFSU switched between two options: DAF and sedimentation. For the treatment of algal-rich water or low-turbidity water (0–20 NTU), the recycling ratio of the DAF was set to 8–10%. The DAF process was run by opening scraper A and valve B. The effluent of this process was collected by a conduit set at the bottom of the SFIPS. However, the DAF process would not perform well when the turbidity was greater than 20 NTU. In such cases, the sedimentation process was launched with the opening of scraper B and valve A, as well as the closing of the dissolved air canister, scraper A and valve B.

Experimental design and mathematical model

To describe the interactive effects of the variables studied on the process and eliminate systematic errors while estimating

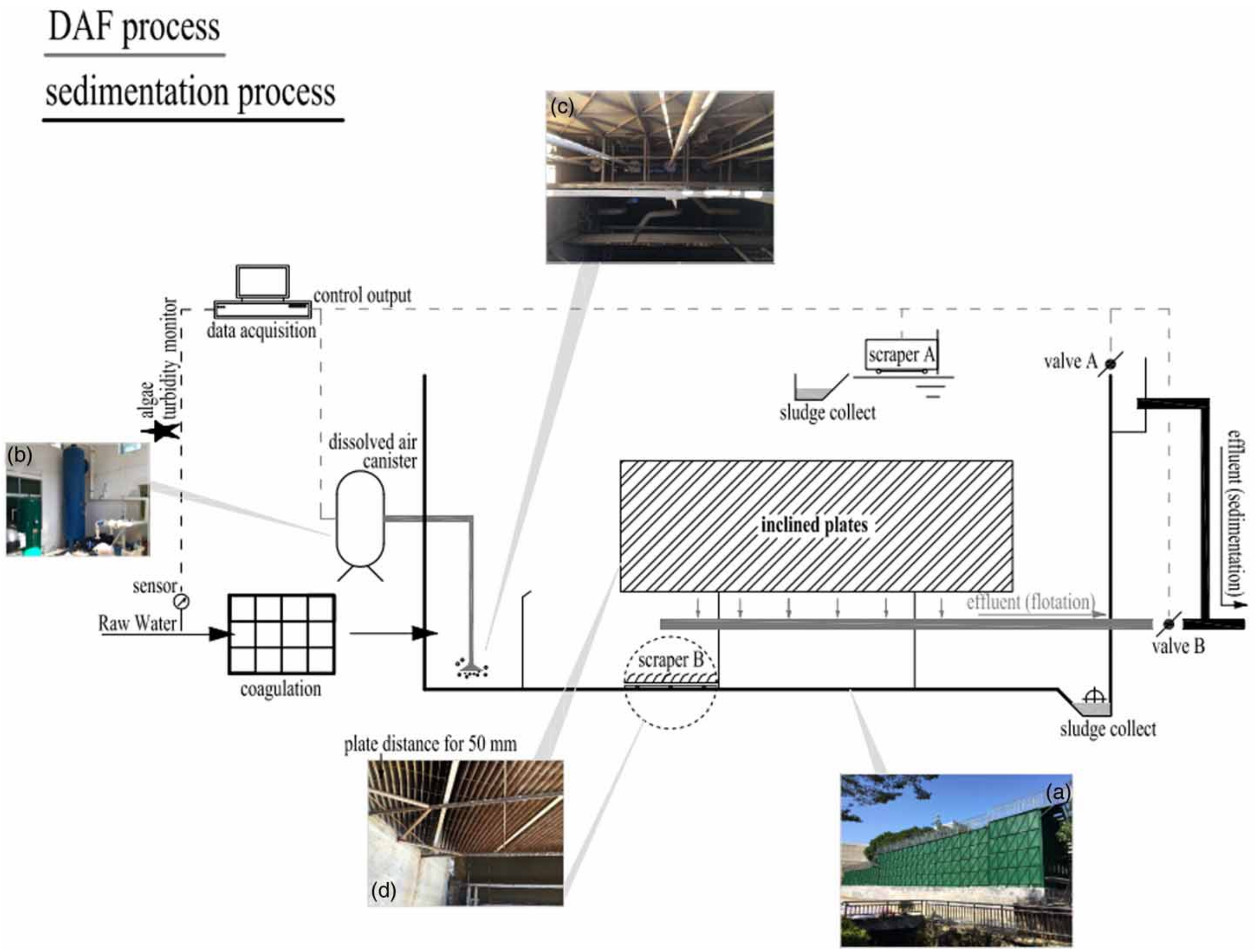

Figure 1 | Flow diagram of the integrated flotation and sedimentation unit (IFSU). Thumbnail (a) shows the exterior of the IFSU, (b) is a snapshot of the dissolved air canister, (c) is a close-up view of the DAF releaser and (d) displays the side flow-inclined plates and scraper.

the experimental error and minimizing the number of experiments needed, the central composite design was applied (Kontogiannopoulos *et al.* 2016). Categorical factors can also be added to this design, which will cause the number of runs generated to be multiplied by the number of combinations of the categorical factor levels. The *Design Expert* software (Stat-Ease Inc., version 8) was used for the statistical design of experiments and data analysis.

Three independent numerical variables, PAC dose, NaOH dose and Tur_{in}, along with SFIPS as a categorical factor, were selected for the treatment of turbidity design. For treatment of algal-rich water, Chl_{in} concentration replaced Tur_{in} as the independent numerical variable, while the other independent numerical variables (PAC dose and NaOH dose) and categorical factors were employed in the turbidity experiment design. To fix conditional experiments, the deviation allowance of Tur_{in} or Chl_{in} was set to ±5%, while PAC dose and NaOH dose were adjusted according to Tur_{in} or Chl_{in}. The design consisted of 2^k factorial points augmented by 2^k axial points and a center point, where k is the number of numerical variables. Based on the numerical variables, 20 experiments $(= 2^k + 2k + 6)$ were designed, with 15 experiments organized in a factorial design (including nine factorial points, six axial points and one center point), and the remaining five involving replication of the central point to obtain a good estimate of the experimental error.

Because a categorical variable (SFIPS) in two levels has also been considered, 40 experiments were conducted. The range and levels of the variables in coded and actual units

Table 2 | Experimental range and levels of independent variables. Chl_{in} indicates influent chlorophyll and Tur_{in} indicates influent turbidity

Type of variables	Name of variables	Range and level		
		−1	0	1
	Treatment for algal-rich water			
	PAC mg/l	4	8	12
	NaOH mg/l	2	6	10
	Chl_{in} mg/l	1,000	4,000	7,000
	Treatment for low turbidity water			
Numerical	PAC mg/l	4	5	6
	NaOH mg/l	1.6	2.6	3.6
	low-Tur_{in} NTU	4	12	20
	Treatment for high turbidity water			
	PAC mg/l	4	22	40
	NaOH mg/l	2	8.5	15
	high-Tur_{in} NTU	20	110	200
Categorical	Side flow inclined plate settlers (SFIPS)	Two levels (with SFIPS (+) and without SFIPS (−))		

are given in Table 2, and its deviation allowance was set to ±5%. As in Table 2, Tur_{in} and Chl_{in} were the original data of raw water during 2010–2013. Herein, the corresponding responses values (the removal efficiency of chlorophyll, turbidity, COD_{Mn} and NH_4-N) were documented, only when the levels of Tur_{in} and Chl_{in} meeting the permutation of variables in Supplementary Material Tables S1–S3 (available with the online version of this paper). Turbidity, COD_{Mn} and NH_4-N removal efficiency were measured or calculated as responses to treatment for turbidity, while turbidity, COD_{Mn}, NH_4-N and chlorophyll removal efficiency were evaluated as responses to treatment of algal-rich water. The experimental conditions and results obtained for treatment of algal-rich water, low-turbidity water and high-turbidity water are shown in the Supplementary Material.

After conducting the experiments, the coefficients of the polynomial model were calculated as follows (Khuri & Cornell 1996):

$$Y = \beta_0 + \beta_i X_i + \beta_j X_j + \beta_{ii} X_i^2 + \beta_{jj} X_j^2 + \beta_{ij} X_i X_j + \dots \quad (1)$$

where i and j are the linear and quadratic coefficients, respectively, and β is the regression coefficient. Analysis of variance (ANOVA) was used for graphical analyses of the data to obtain the interaction between the process variables and the responses. The P value with a 95% confidence level was considered to indicate the effectiveness of the model terms.

Analytical methods

Chlorophyll was determined using the method described by María et al. (2012) and calculated using Liechtenthaler equations (Lichtenthaler 1987). Turbidity was measured using a Hach 2100P turbidity meter (Hach Co., Loveland, Colorado, USA). NH_4-N was analyzed by the colorimetric method according to *Standard Methods* (Nessler Method) (APHA New York 2005). The method USEPA (1983) was applied to determine COD_{Mn}.

RESULTS AND DISCUSSION

Results

Model fitting and statistical analysis

Two IFSU reactors, one with and the other without SFIPS, were applied to conduct the aforementioned experiment. The experimental conditions and results for the two IFSU reactors are shown in Supplementary Tables S1–S3, while different degree polynomial models were also presented in Supplementary Table S4 (available with the online version of this paper).

Reactor performance

The ANOVA data for chlorophyll removal responses are shown in Supplementary Table S4. The experimental data were fitted to a reduced quadratic model. Figure 2(a)–2(b) shows the 3D surface plots of the response as a function of PAC and NaOH dose at the mean level of Chl_{in} for SFIPS and non-SFIPS IFSU systems. Comparison of the results presented in Figure 2(a) along with those in Figure 2(b) revealed that the SFIPS had an increasing impact on the mean level of Chl_{in} (4,000 mg/l). As shown in Figure 2(c), there was good convergence between the experimental and predicted values of the chlorophyll removal efficiency. The interaction between SFIPS and PAC is presented in Figure 2(d), while the interaction between SFIPS and

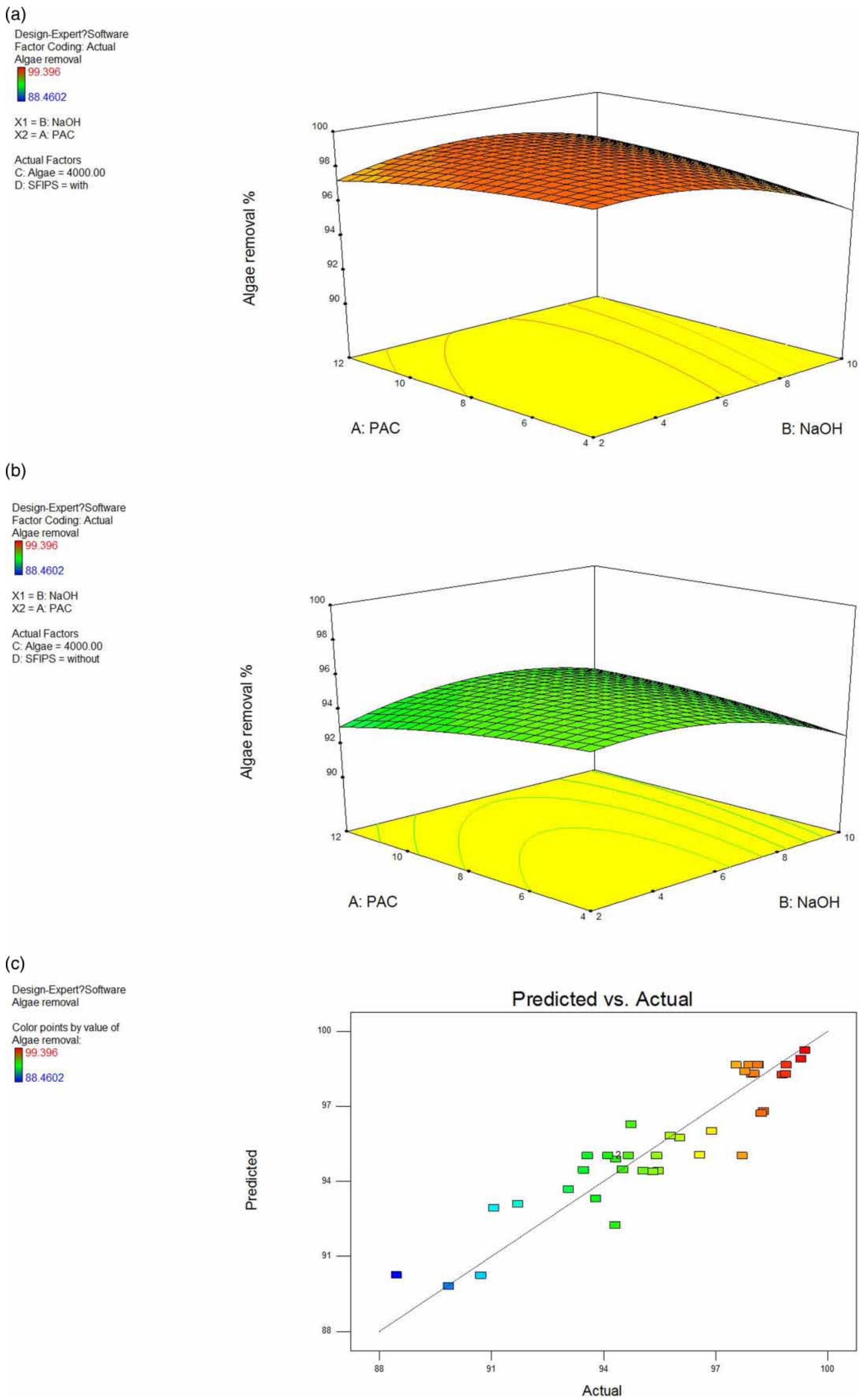

Figure 2 | Response surface plots for chlorophyll removal as a function of PAC and NaOH at Chl_{in} concentration of 4,000 mg/l (a) with SFIPS and (b) without SFIPS; (c) plot of predicted vs. actual values for chlorophyll removal; (d) interactive effects of PAC-SFIPS on chlorophyll removal at a NaOH dose and Chl_{in} level of 4 mg/l and 4,000 mg/l, respectively; interactive effects of NaOH-SFIPS on chlorophyll removal at a PAC dose and Chl_{in} level of (e) 8 mg/l and (f) 4,000 mg/l. (*Continued*.)

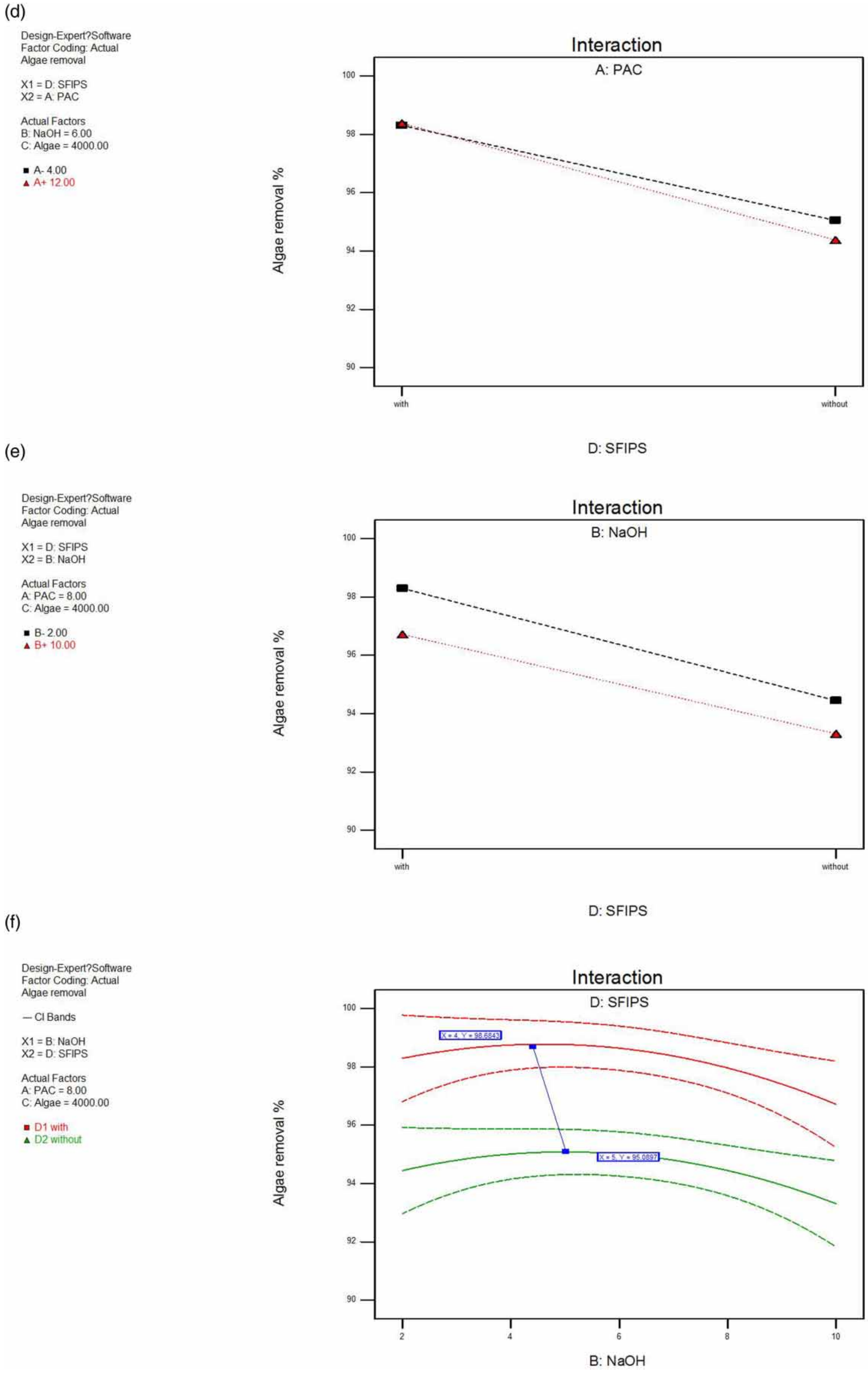

Figure 2 | Continued.

NaOH is depicted in Figure 2(e)–2(f). According to the aforementioned interactional diagrams in Figure 2, higher chlorophyll removal efficiency (in Figure 2(d), 98.3% with SFIPS comparing to 95.1% without SFIPS at condition of 4 mg/l PAC and 6 mg/l NaOH, while 98.1% with SFIPS comparing to 93.6% without SFIPS at condition of 12 mg/l PAC and 6 mg/l NaOH; in Figure 2(e), 98.5% with SFIPS comparing to 94.4% without SFIPS at condition of 8 mg/l PAC and 2 mg/l NaOH, while 96.7% with SFIPS comparing to 93.5% without SFIPS at condition of 8 mg/l PAC and 10 mg/l NaOH) was documented in the presence of SFIPS.

Instability of effluent turbidity is the main problem associated with DWTPs, especially when they are operating at high loading in the face of seasonal variations in raw water characteristics. Figure 3(a)–3(b) shows the 3D surface plots of PAC and NaOH with respect to turbidity for the treatment of low-turbidity water (0–20 NTU) using the DAF process. As shown in Figure 3, the SFIPS had an increasing effect on response at the mean Tur_{in} (12 NTU). However, it should be noted that an increasing effect of PAC dose and decreasing effect of NaOH dose were found at Tur_{in} of 12 NTU. Figure 3(c)–3(d) show similar trends with different values. Figure 3(e) reveals relatively good agreement between the experimental and predicted values of turbidity removal ($R^2 = 0.8615$ in Supplementary Table S4).

The results of ANOVA for the treatment of high-turbidity water (20–200 NTU) using the sedimentation process are presented in Supplementary Table S4. The NaOH dose was the minor impact factor and is shown in Figure 4(a)–4(b). As shown in Figure 4(c), there was good agreement between the predicted and actual data ($R^2 = 0.9519$ in Supplementary Table S4). In the presence of SFIPS (Figure 4(d)), the higher turbidity removal (94.0% with SFIPS comparing to 88.9% without SFIPS at condition of 40 mg/l PAC and 8.5 mg/l NaOH, while 80.1% with SFIPS comparing to 70.1% without SFIPS at condition of 4 mg/l PAC and 8.5 mg/l NaOH) was recorded, which is in accordance with the results of previous studies (Tarpagkou & Pantokratoras 2014; Ren *et al.* 2017). Owing to the increased surface area and decreased settling distance, sedimentation processes with SFIPS is able to separate particles more rapidly than conventional settlers (Laskovski *et al.* 2006; Sarkar *et al.* 2007). As shown in Figure 4(d), the maximum turbidity removal (94.3%) was found under SFIPS and the highest PAC dose (40 mg/l). High doses of flocculant are always necessary when treating high-turbidity water.

As shown in Supplementary Tables S1–S3, the ratios of the minimum to maximum COD_{Mn} removal were 31.07%: 61.68%, 27.81%:62% and 16.18%:66.33% during the treatment of algal-rich water, low-turbidity water and high-turbidity water, respectively. In the presence of SFIPS, there was an advantage for COD_{Mn} removal with the SFIPS over the non-SFIPS (in Figure 5(a), 54.3% with SFIPS compared with 44.2% without SFIPS at condition of 4 mg/l PAC and 6 mg/l NaOH, while 53.8% with SFIPS compared with 42.1% without SFIPS at condition of 12 mg/l PAC and 6 mg/l NaOH; in Figure 5(b), 42.5% with SFIPS compared with 38.8% without SFIPS at condition of 4 mg/l PAC and 2.6 mg/l NaOH, while 38.3% with SFIPS compared with 34.9% without SFIPS at condition of 6 mg/l PAC and 2.6 mg/l NaOH; in Figure 5(c), 66.1% with SFIPS compared with 55.7% without SFIPS at condition of 40 mg/l PAC and 8.5 mg/l NaOH, while 39.7% with SFIPS compared with 32.3% without SFIPS at condition of 4 mg/l PAC and 8.5 mg/l NaOH). Comparison of the results presented in Figure 5(a)–5(c) revealed that a high-level PAC dose (12 mg/l PAC in the treatment of algal-rich water, while 6 mg/l PAC in the treatment of low-turbidity water) had a decreasing effect on COD_{Mn} removal during the DAF process, while it showed increasing impact during the sedimentation process.

In terms of NH_4-N removal, the DAF process was more effective than the sedimentation process. The minimum to maximum ratios were 25.31%:66.59% and 30.23%:72.15% for treatment of algal-rich water and low-turbidity water, respectively (Supplementary Tables S1–S2). However, the NH_4-N removal ratio obtained during the treatment of high-turbidity water was only 10.9%:32.47% (Supplementary Table S3). As shown in Figure 6, the effects of SFIPS on NH_4-N removal were similar to those observed for COD_{Mn} removal.

DISCUSSION

When SFIPS (Figures 2–4) was used, IFSU could improve the removal ratio of algae or turbidity separation. The effects of SFIPS occurred via the release of saturated dissolved

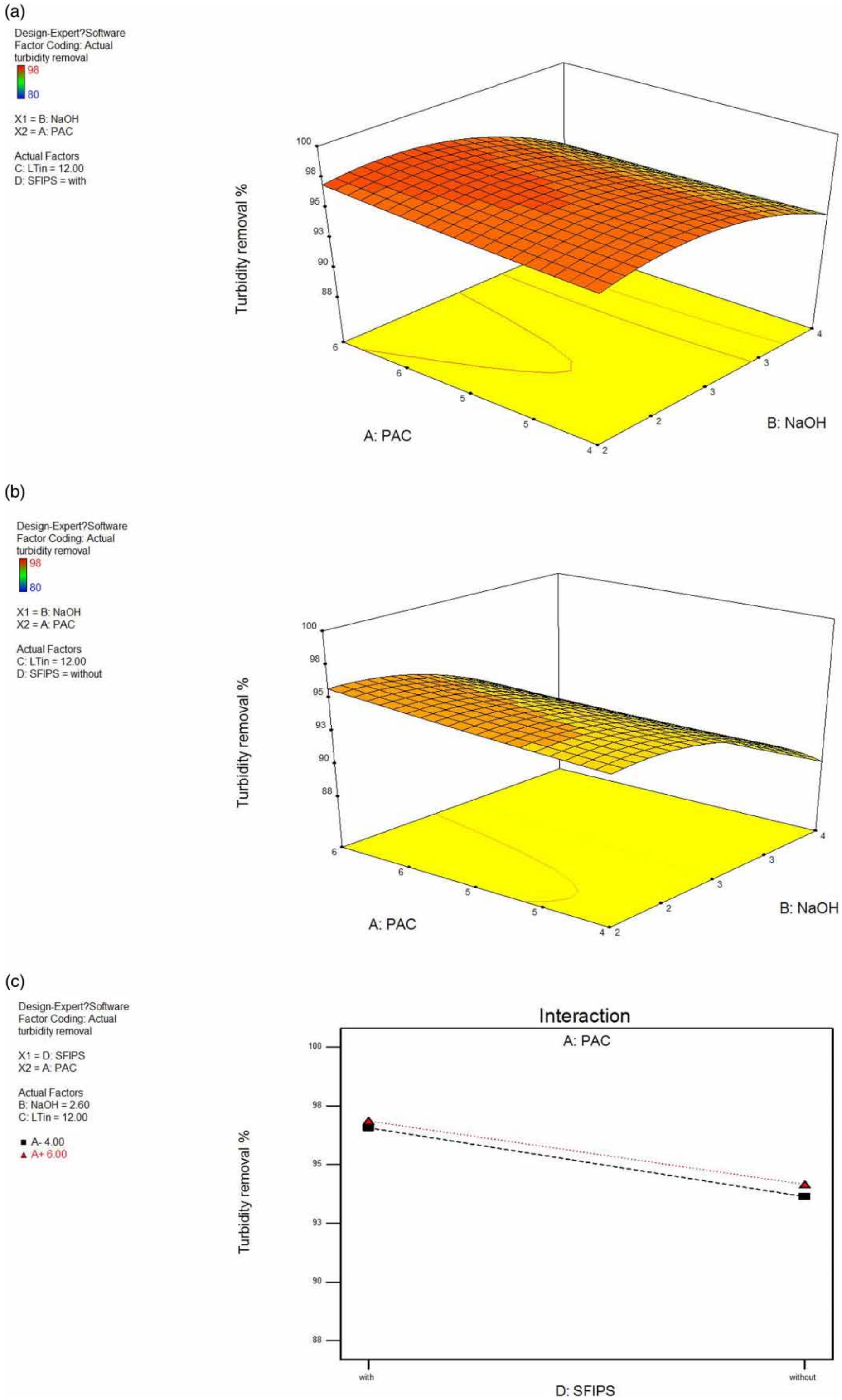

Figure 3 | Response surface plots for turbidity removal as a function of PAC and NaOH at Tur_{in} of 12 NTU (a) with SFIPS and (b) without SFIPS; (c) interactive effects of PAC-SFIPS on turbidity removal at a NaOH dose and Tur_{in} of 2.6 mg/l and 12 NTU, respectively; (d) interactive effects of NaOH-SFIPS on turbidity removal at a PAC dose and Tur_{in} of 5 mg/l and 12 NTU, respectively; (e) plot of predicted vs. actual values for turbidity removal. (*Continued*.)

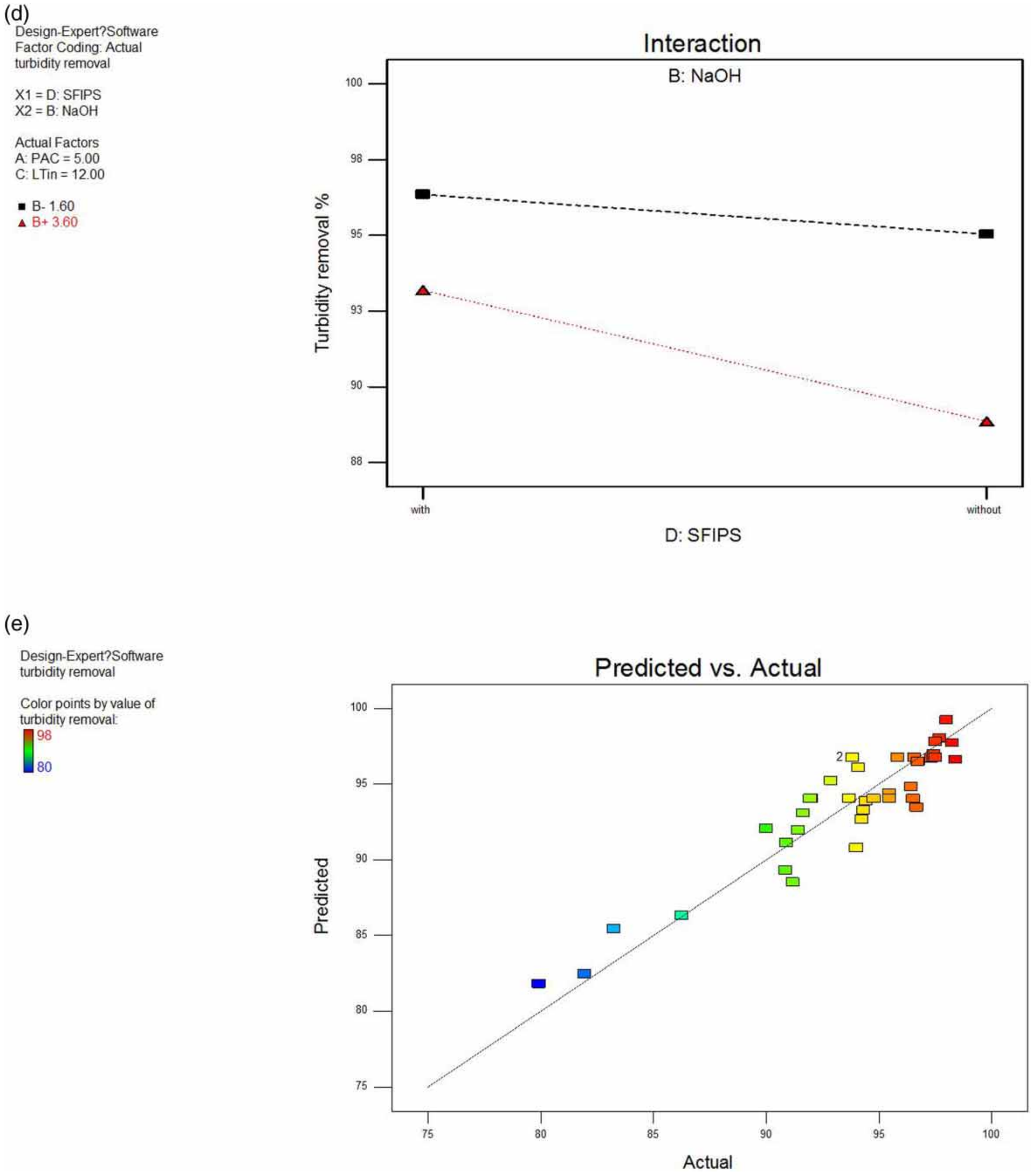

Figure 3 | Continued.

water into the contact zone during the DAF process, which generated bubbles that caused floc-bubble-aggregates to rise to the surface of the tank (Edzwald 2010). Inside the SFIPS, some small bubbles would aggregate into large bubbles, therefore, small bubbles formed directional upflow along the lower sides of the SFIPS, while large bubbles provided non-directional flow along the upper sides of the SFIPS (Xing *et al.* 2006). Hence, large bubbles generated more lifting floc-bubble-aggregates than small bubbles. Consequently, the SFIPS investigated in our experiments functioned as a counterflow inducer.

The velocity of the floc-bubble-aggregates in the upper part of the separation zone was also simulated using a waterproof microscope video and computational fluid dynamics during the DAF process (Figure 7) (Li *et al.* 2017). Prior to the separation zone, we set a baffle to obtain a height of 3.8 m between the surface and the top edge of the baffle. The height produced a cross-flow (above the baffle) water

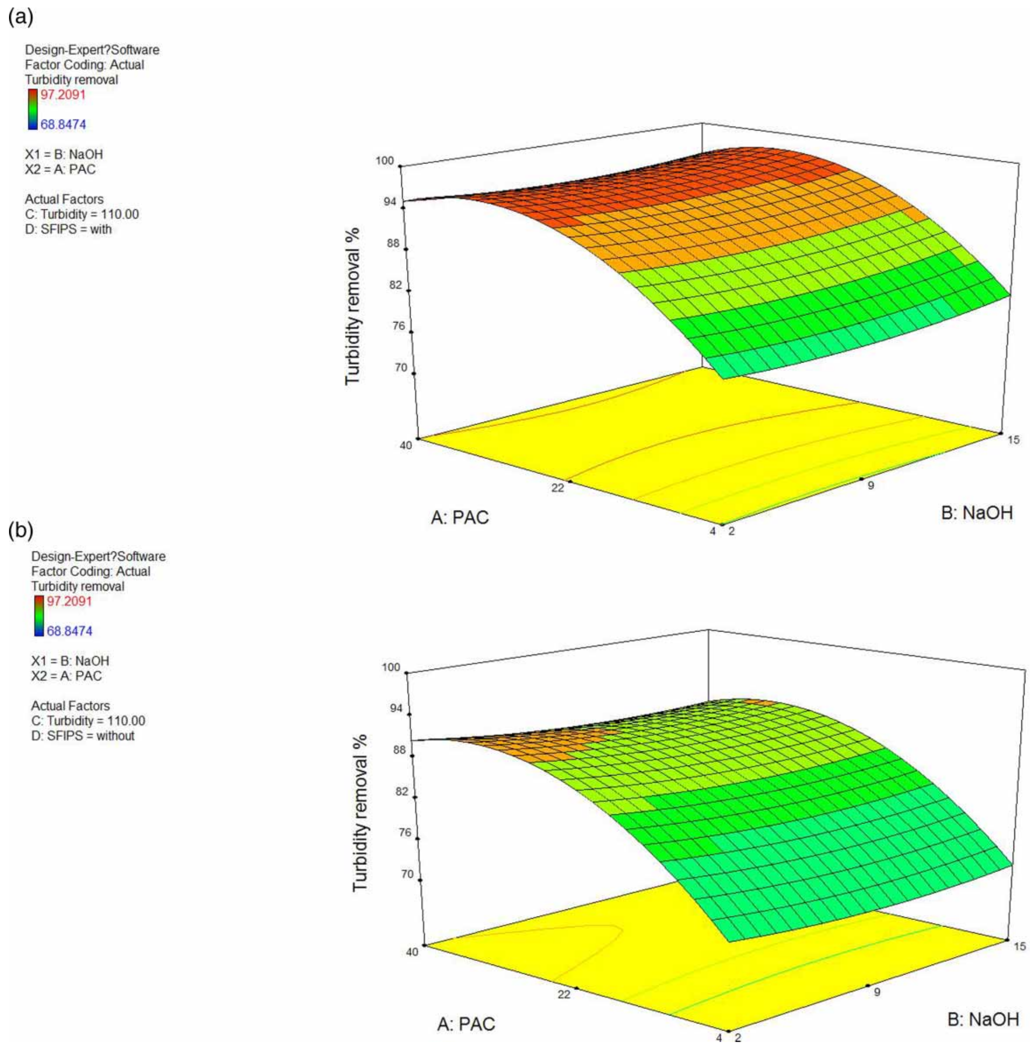

Figure 4 | Response surface plots of turbidity removal as a function of PAC and Tur_{in} at a mean level of NaOH (8.5 mg/l) (a) with SFIPS and (b) without SFIPS; (c) plot of predicted vs. actual values for turbidity removal; (d) interactive effects of PAC-SFIPS on turbidity removal at a NaOH dose and Tur_{in} of 8.5 mg/l and 200 NTU, respectively (*Continued*.)

velocity of approximately 200.8 m/h (55.8 mm/s, see Figure 7). These findings were in accordance with those of Lundh *et al.* (2002), who found that 37 m/h or greater water velocity (above the baffle) favored development of stratified flow in the separation zone. As shown in Figure 7, the highest velocity was found at the most distant point of the separation zone from the contact zone.

This streamlined distribution would conform to the stratified flow pattern of DAF, which was provided by Hazen theory and previous studies by Edzwald *et al.* (1999; Edzwald 2007). As shown in the conceptual picture of the stratified flow pattern (Figure 8), the horizontal flow near the top of the tank provides a certain clarification area (length × width of the separation zone), which is doubled with the return flow, and then finally tripled with the vertical flow toward the bottom. If one has three flow paths such as this, the clarification hydraulic loading is 1/3 the separation zone loading. In other words, a separation zone loading of 30 m/h reduces to 10 m/h in terms of the Hazen clarification loading (Edzwald 2010). Therefore, we deduced that SFIPS would greatly enhance the effects of the stratified flow pattern and decrease the clarification loading rate in the separation zone during the DAF process, leading to improvement of the algal-rich water and low-turbidity water. With the constant inflow during the DAF process in the IFSU, SFIPS would drastically decrease clarification

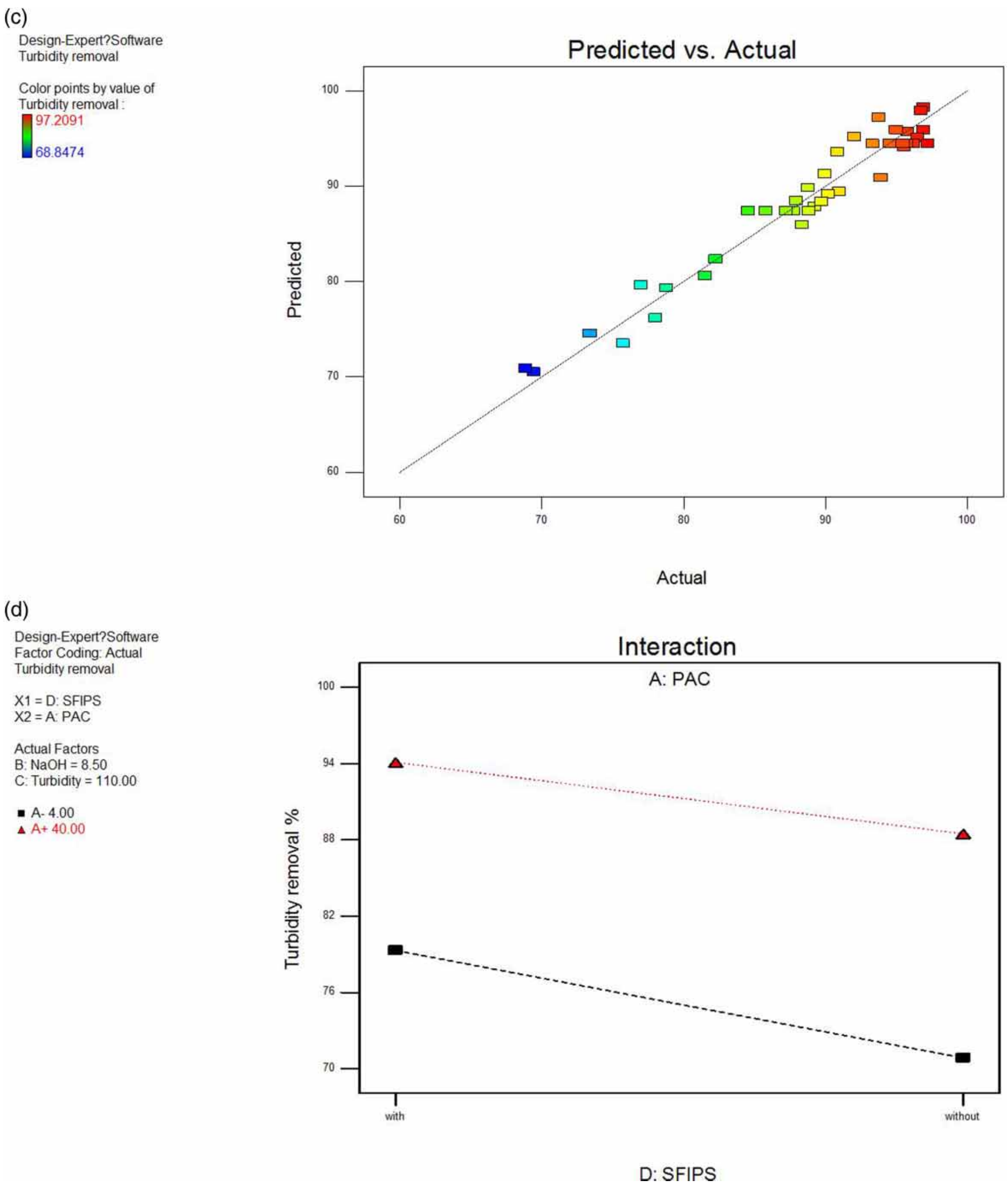

Figure 4 | Continued.

hydraulic loading, which would increase the retention time of saturated dissolved water and the contact between saturated dissolved water and COD_{Mn} or NH_4-N in the IFSU. These changes would account for the higher removal ratio of COD_{Mn} and NH_4-N from IFSU with SFIPS.

Good coagulation chemistry depends on coagulant dose and pH, with the optimum conditions producing flocs with a charge near zero of zeta potentials and relatively high hydrophobicity. Nevertheless, our study showed that too much NaOH would hinder the removal ratio of algae and low turbidity (see Figures 2(e), 2(f) and 3(d)) during DAF. Since air bubbles is non-polar molecules and exert a negative charge in waters. These negative charges expressed negative zeta potentials, which is attributed to smaller anions that reside at the bubble–water interface at a greater concentration than larger hydrated cations (Edzwald 2010). Therefore, we hypothesized too much NaOH would release abundant hydrated cations,

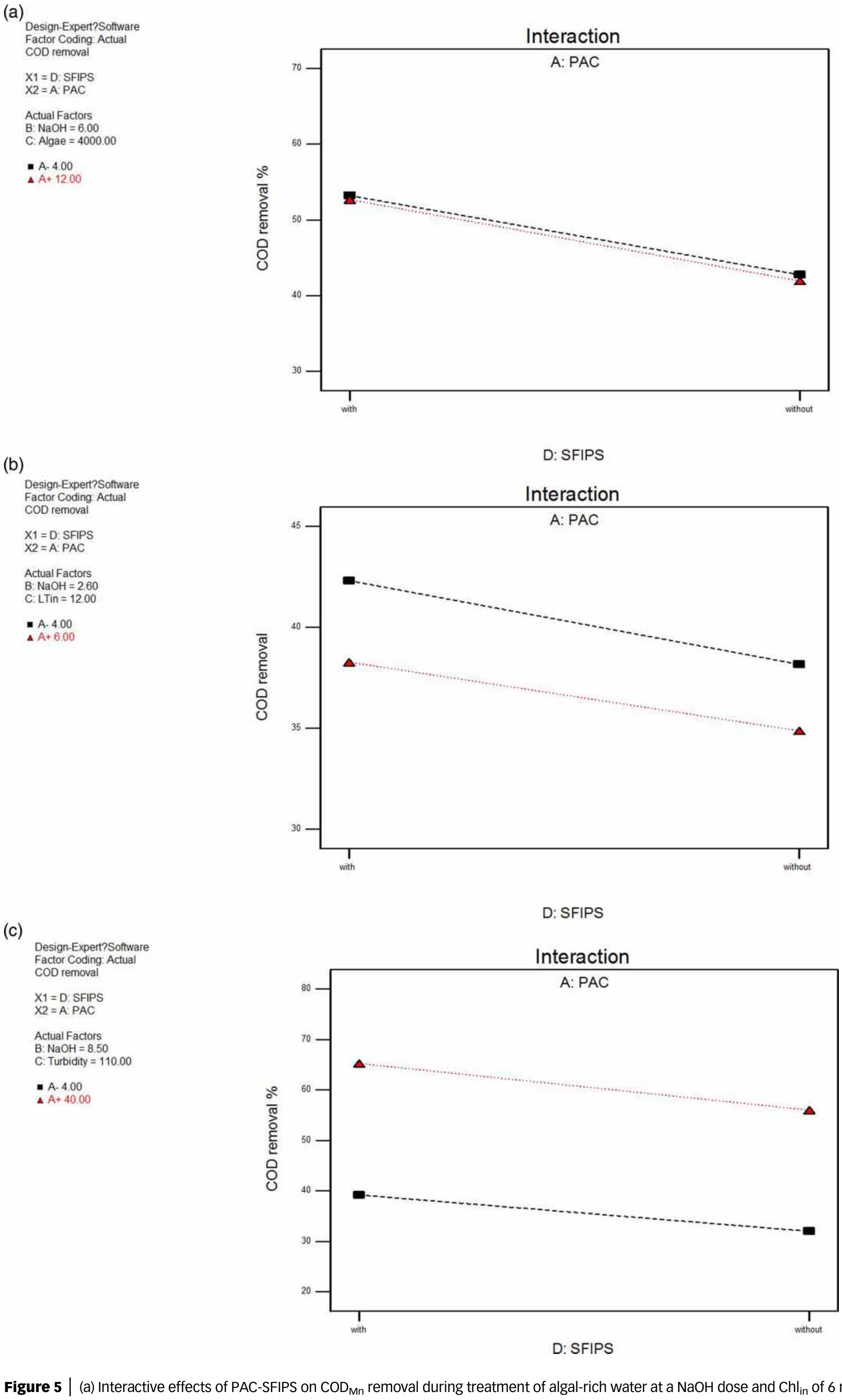

Figure 5 | (a) Interactive effects of PAC-SFIPS on COD_{Mn} removal during treatment of algal-rich water at a NaOH dose and Chl_{in} of 6 mg/l and 4,000 mg/l, respectively; (b) interactive effects of PAC-SFIPS on COD_{Mn} removal during treatment of low-turbidity water at a NaOH dose and Tur_{in} of 2.6 mg/l and 12 NTU, respectively; (c) interactive effects of PAC-SFIPS on COD_{Mn} removal during treatment of high-turbidity water at a NaOH dose and Tur_{in} of 8.5 mg/l and 110 NTU, respectively.

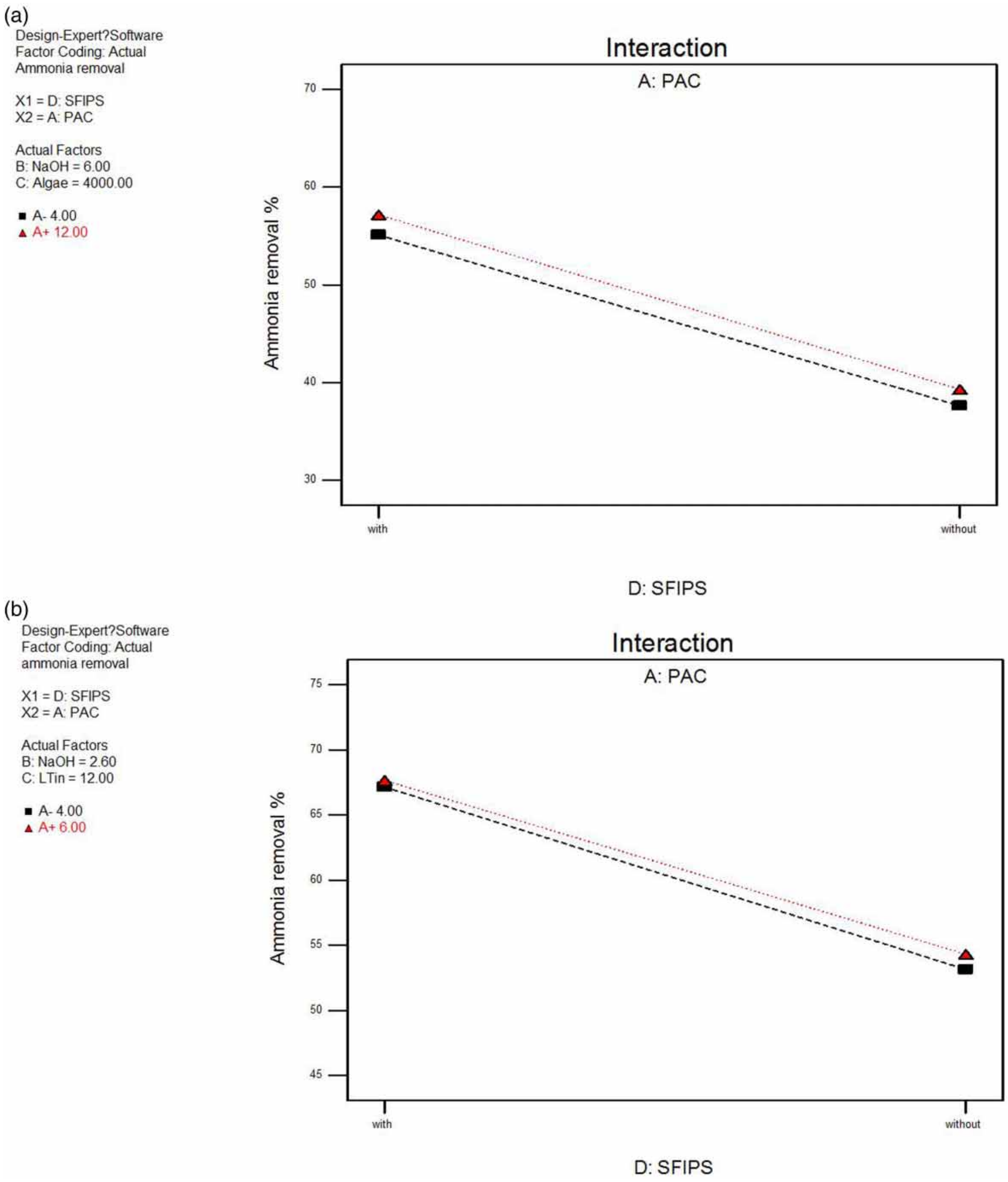

Figure 6 | (a) Interactive effects of PAC-SFIPS on NH_4-N removal during treatment of algal-rich water at a NaOH dose and Chl_{in} of 6.0 mg/l and 4,000 mg/l, respectively; (b) interactive effects of PAC-SFIPS on NH_4-N removal during treatment of low-turbidity water at a NaOH dose and Tur_{in} of 2.6 mg/l and 12 NTU, respectively.

which squeezing out anions and changing the bubble–water interface from negative zeta potentials to positive zeta potentials. Consequently, the positively charged bubble–water interface would affect the interaction between bubble and PAC particle floc, which lead to the lower removal ratio obtained from flocs with high NaOH dose during DAF. However, more micro-data need to be analyzed to elucidate the above experiment result.

In terms of treating high-turbidity water via IFSU, the performance of the sedimentation process was equivalent to that of other settling plants, and it overcame the ineffectiveness of the DAF process for treatment of high-turbidity water. The IFSU integrates the flotation and sedimentation process in a single unit, therefore, it has a smaller plant footprint, which is a significant advantage for facilities in large cities. Moreover, the need for only one structure for DAF

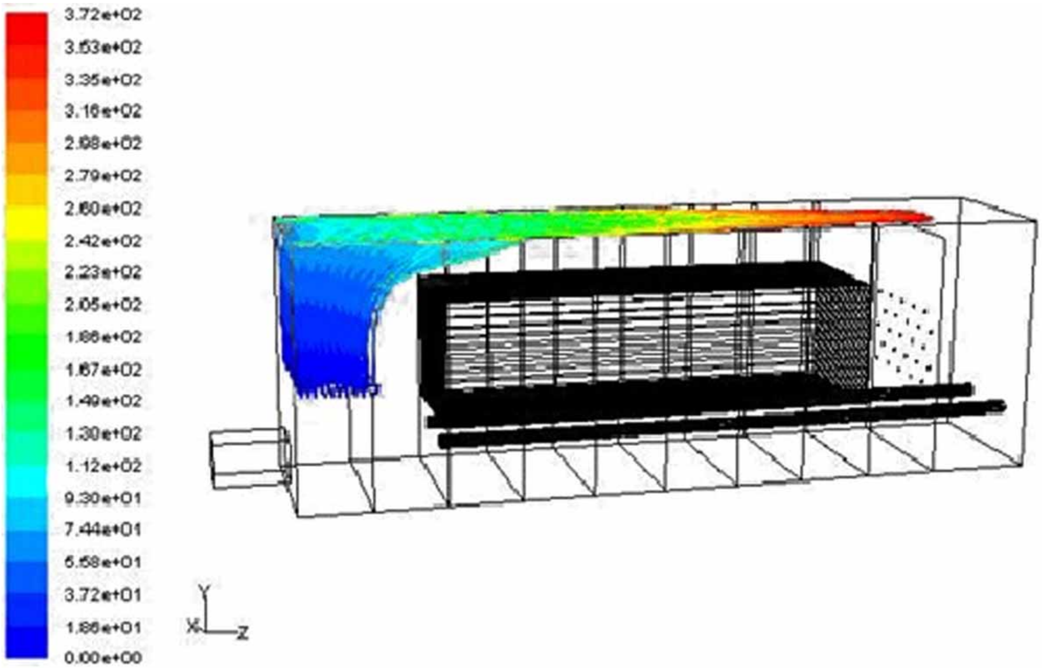

Figure 7 | Velocity of particles in the upper part of the IFSU separation zone during the DAF process.

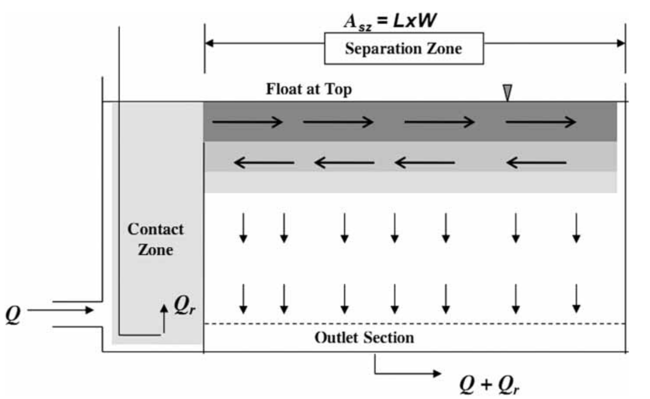

Figure 8 | Conceptual horizontal stratified flow pattern near the top of the separation zone and vertical plug flow below the bubble blanket. Reprinted from Edzwald (2010).

and settling reduces costs when compared with those of conventional plants, which have a horizontal layout of separate units.

CONCLUSION

This study presents new findings regarding the application of IFSU to the treatment of algal-rich, low-turbidity and high-turbidity water. The results revealed a significant positive effect of SFIPS on the IFSU performance. SFIPS functioned as a counterflow inducer, which enhanced the effects of stratified flow and decreased the clarification-loading rate in the separation zone during the DAF process. The IFSU with SFIPS improved the removal ratio of algae, turbidity and COD_{Mn}. Moreover, the RSM model derived in this study could describe the variations in the process as a function of the variable studied. However, application of the RSM models was limited to the range of the variables studied. Therefore, to predict the IFSU performance under conditions outside of the range studied or under different operating conditions, additional experiments are needed to verify the model under the desired conditions. This study also showed that the use of IFSU with SFIPS is a new window to introduce a promising and economical method to enable the upgrade of conventional DWTPs.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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