J Water SRT — Aqua Vol. 48, No. 5, pp. 211–217, 1999

Fuzzy control of a coagulation reaction for the treatment of high-turbidity water

M. D. Wu and J. C. Liu* *Department of Chemical Engineering, National Taiwan University of Science and Technology, 43 Keelung Road, Section 4, Taipei 106, Taiwan*

ABSTRACT: A fuzzy logic controller (FLC) was used for the automatic control of coagulation reactions. A laboratory-scale water treatment plant (rapid mixing, flocculation and sedimentation), operated under continuous-flow mode, was used to simulate reaction conditions. Streaming current (SC) and pH were chosen as process outputs; while alum and base doses were chosen as control process inputs. They were monitored on-line, and transduced through an FLC. Using raw water with initial turbidity of 600 NTU, a residual turbidity of less than 2.5 NTU was obtained. Raw water with an ultra-high initial turbidity (a kaolinite concentration of 1000 mg/dm^3) was also tested. A residual turbidity of less than 6 NTU was obtained under these conditions. In addition, for the study of dynamic responses of the system to shock loadings, raw water with an initial turbidity of 798 NTU was spiked with 1 dm^3 of 100 g/dm^3 kaolinite suspension. The system was first perturbed by the impulse input of solid loading, and its residual turbidity increased to 16 NTU. However, the system rapidly regained stability, and a residual turbidity of less than 8 NTU could be obtained. It was demonstrated that the fuzzy logic controller functions satisfactorily and is robust in the treatment of water of ultra-high turbidity.

INTRODUCTION

Situated in the Pacific rim region, Taiwan suffers, on average, typhoon attacks three to five times each summer. The accompanying rain storm often turns into floods or excessive surface runoff that contains huge amounts of suspended solids and organic compounds. In normal situations drinking water quality is guaranteed by water treatment plants equipped with typical processes consisting of aeration, coagulation and flocculation, sedimentation, rapid sand filtration, and postchlorination. However, raw water quality in water supply reservoirs deteriorates rapidly during typhoons. Even experienced engineers in water treatment plants find it difficult to handle water with ultra-high turbidity caused by typhoons. Common measures that local engineers take in response to the emergency condition include [1]:

- Introduction of prechlorination to remove pathogens;
- Application of polymer as a coagulant aid;
- Increase of chlorine dose in the postchlorination unit;
- Advice to consumers to boil water for longer period;
- Water supply cut off until water quality is restored.

The shortcomings of the current countermeasures are obvious. First, consumers complain of turbid water with an unpleasant smell and odour. Second, the high chlorine dose used in the prechlorination and postchlorination units inevitably increases DBPs concentration and the related health risks [2]. Third, the quality of water cannot in fact be guaranteed, as evidenced by the official record that all violations of maximum allowable limit (MCL) of turbidity occurred during typhoons [1]. Since typhoons are routine in Taiwan during the summer and autumn, managers and engineers of water treatment plants are used to the emergency conditions that arise. Emergency operation planning includes: encouraging consumers to store spare water in advance of a typhoon, back-up power sources in the plants, an enhanced leakage detection and repair programme, intensive water quality examination, and the protection of equipment from flooding. Nevertheless, the determination of proper a coagulant dose remains one of the most difficult tasks, taking into account that turbidity of raw water often reaches over 1000 NTU, sometimes even several times higher during typhoon. Take typhoon 'Wayne' that struck Taiwan on 16 June 1996 for example, raw water turbidity reached as high as 4000 NTU and was $\approx$800 NTU in the following weeks in the major water supply reservoir of metropolitan Taipei. Proper dosing of coagulant is difficult to decide, simply because the raw water quality was so poor and unpredictable that no quick and simple engineering method works. In fact, it has been shown that highly turbid waters occur quite widely in other parts of the world and present considerable treatment problems, and the addition of polymeric flocculants could enhance sedimentation [3]. High-turbidity water is also found seasonally in some African countries, and a pretreatment technique has been studied there [4]. To deal with this problem, a better control of coagulation reaction therefore becomes critical, especially when facing a dynamic, unexpected condition. Consequently, there has always been a strong interest in developing automatic dose control systems

*To whom correspondence should be addressed: Tel.: 886 2 2737 6627, Fax: 886 2 2737 6644, E-mail: liu@ch.ntust.edu.tw

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for water treatment plants in Taiwan [5–7]. Benefits of good coagulation control include:

- better response toward unexpected conditions and shock loadings;
- consistency and improvement in water quality;
- smaller amount of sludge generated;
- cost-effectiveness.

In fact, the automatic control of water treatment plants has found increasing application world-wide, due to the rapid development and progress in computer software and control theory [8]. Several approaches have proved successful, including the fuzzy control of coagulation reactions in a water treatment plant in Japan [9], information processing coupled with expert systems for water treatment plants [10], neural networks in water and wastewater treatment plant [11], and pH adjustment [12]. Among all the control theories described, fuzzy control has found wide application and proved to be superior in performance to conventional systems [13], especially for ill-defined systems or for systems where no accurate mathematical models exist to describe them [14]. A fuzzy logic controller (FLC) is best applied to nonlinear, time-variant and ill-defined systems [15].

Difficulties exist in proper coagulation control such as changes in raw water quality, time limits for jar test, and a broad range of coagulant chemicals [16]. The time-consuming manipulation in finding the optimum dosage is very difficult for water which undergoes large turbidity variations [17]. It is generally agreed that the sound control of coagulation reactions always requires a good control of pH and coagulant dose, which is achieved through jar testing and zeta potential measurement [18]. A sophisticated control algorithm is essential when utilising residual turbidity as the performance index. In addition, pH-related complexities are encountered, since both an inorganic coagulant and a pH-control chemical would affect pH values [16].

In our previous study [6] we demonstrated that coagulation reactions under normal conditions can be well controlled through the combination of a fuzzy logic controller (FLC) and a streaming current detector (SCD). As an extension of this work, the major objective of our current work is to investigate the performance and robustness of the system for the treatment of high-turbidity water under shock-loading conditions.

METHODS AND MATERIALS

Since most aluminium species are positively charged, their adsorption on the negatively charged clay colloid surface brings about charge neutralisation. In this case, the zeta potential is a useful parameter for coagulation process control [17]. We have conducted on-line monitoring of streaming current (SC), and have established its correlation to zeta potential [6]. Residual turbidity is chosen as the performance index, which is affected by streaming current (SC) and pH. It is noted that residual turbidity does not always correlate well with streaming current (SC). However, in the present case of high turbidity waters, where charge neutralisation is the predominant destabilisation mechanism, then SC should be a useful guide to optimum dosages. Meanwhile, streaming current (SC) is a function of the coagulant dose and the pH. In addition, coagulant (either alum or ferric salts) dose would change the pH. The system identification is therefore conducted through monitoring process output of streaming current (SC) and pH. The objective is to minimise residual turbidity through the control input of coagulant and base doses.

When an FLC is applied, a control action is determined by the measurement of process output, the control rules, and the process input. The fuzzification interface involves the following functions [13]:

(a) measure the values of the output variables,
(b) perform a scale mapping that transfers the range of variables into corresponding linguistic values as characterised by respective membership functions,
(c) perform the function of fuzzification that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets.

Thus a fuzzification operator has the effect of transforming crisp data into fuzzy sets. The raw data of process input/output were fuzzified and transformed into fuzzy data, represented by membership functions. The structure and interface of the FLC is described in our previous work [6].

In setting up control rules in the current study, important parameters in coagulation reaction such as residual turbidity, streaming current (SC), pH, coagulant dose and base dose are included. A laboratory-scale water treatment plant, including rapid mixing, flocculation, and sedimentation, was then operated in a continuous-flow mode. The rapid mixing tank is cylindrical, with an inner diameter of 29 cm and a height of 29 cm. It was mixed at 100 r.p.m. by a stirrer (Fargo DC-60M). The retention time of the water in the rapid mix tank was estimated at 2 min. The effluent from the rapid mix tank flows into a flocculator stirred at 20 r.p.m. with an inner diameter of 20 cm and a height of 19.5 cm, and then into a sedimentation tank ($26 \times 20 \times 25$ cm^3). The retention time was between 15 and 20 min in the flocculator, and 40–50 min in the sedimentation tank. A more detailed description, including a flow chart of the laboratory-scale water treatment plant and its operation procedures can be found in [6]. Control rules were developed and modified based on our previous knowledge and from repeated test runs of the laboratory-scale plant.

RESULTS AND DISCUSSION

Persistent high-turbidity water

Results of laboratory-scale water treatment plant operation are shown in Figs 1a to 1d for raw water, with an initial turbidity of 600 NTU, and of medium alkalinity (0.1 g/dm^3 $NaHCO_3$). This is to imitate the persistently high turbidity that is found in

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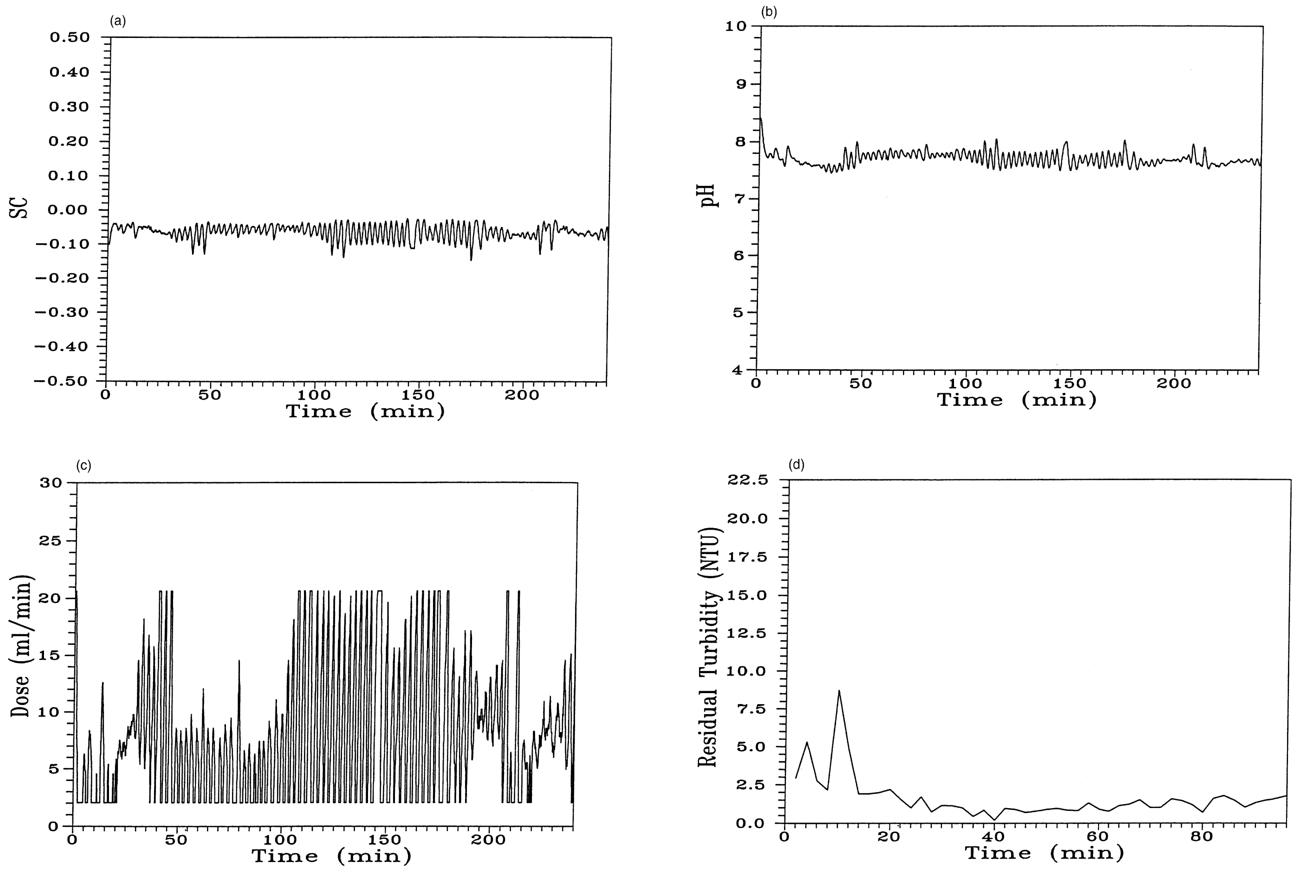

Fig. 1 (a) Streaming current as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 600 NTU, I = 0.001 M $NaClO_4$, $[NaHCO_3]$ = 100 mg/dm^3. (b) Values of pH as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 600 NTU, I = 0.001 M $NaClO_4$, $[NaHCO_3]$ = 100 mg/dm^3. (c) Alum dose as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 600 NTU, I = 0.001 M $NaClO_4$, $[NaHCO_3]$ = 100 mg/dm^3. (d) Residual turbidity as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 600 NTU, I = 0.001 M $NaClO_4$, $[NaHCO_3]$ = 100 mg/dm^3.

reservoir water in the aftermath of typhoon. The control set-point was chosen at an SC of –0.05 and pH of 8.0 [6]. When the coagulation reactor was initially filled with raw water, the kaolinite colloids were negatively charged. The negative reading of SC (Fig. 1a) triggered the input of alum (Fig. 1c). Feeding of the coagulant induced a transition in particle charge towards a nearly neutral condition. Correspondingly, the SC readings changed upon the addition of alum, and then stabilised shortly afterwards at the preset value of –0.05. The addition of NaOH solution stabilised the pH value to the preset value of 8.0 throughout the experiment. During the initial period, the residual turbidity ranged from 2 to 9 NTU (Fig. 1d). The quality of the treated water improved as the system became more stable and the residual turbidity was lower than 2 NTU.

Ultra-high turbidity water

Aside from water with very high turbidity during a typhoon, it has been noted that extremely turbid water can persist all year in Northern China [3], or from a few days to as much as 50% of the year during the monsoon season in tropical countries [4]. To simulate the response of the fuzzy-logic-controlled system under heavy-loading conditions such as occurs in the monsoon season, floods, and first few hours after a typhoon, another experiment was conducted on water with an ultra-high initial turbidity (1000 mg/dm^3 of kaolinite). Results are shown in Figs 2a to 2d. Fluctuations in SC reading which were observed at the beginning, gradually disappeared, and stabilised thereafter (Fig. 2a). In utilising a fluidised pellet bed for the treatment of high-turbidity water, the researchers have pointed out that the adsorption of soluble aqua-aluminium species to clay surfaces may proceed preferentially to bring about charge neutralisation [17]. The SC fluctuations can therefore be interpreted as surface charge variations affected by alum dose. Following alum addition, pH values decreased rapidly, but immediately stabilised at the preset value due to the NaOH dose. It then did not fluctuate significantly, indicating that the pH was well controlled (Fig. 2b). Coagulant dose

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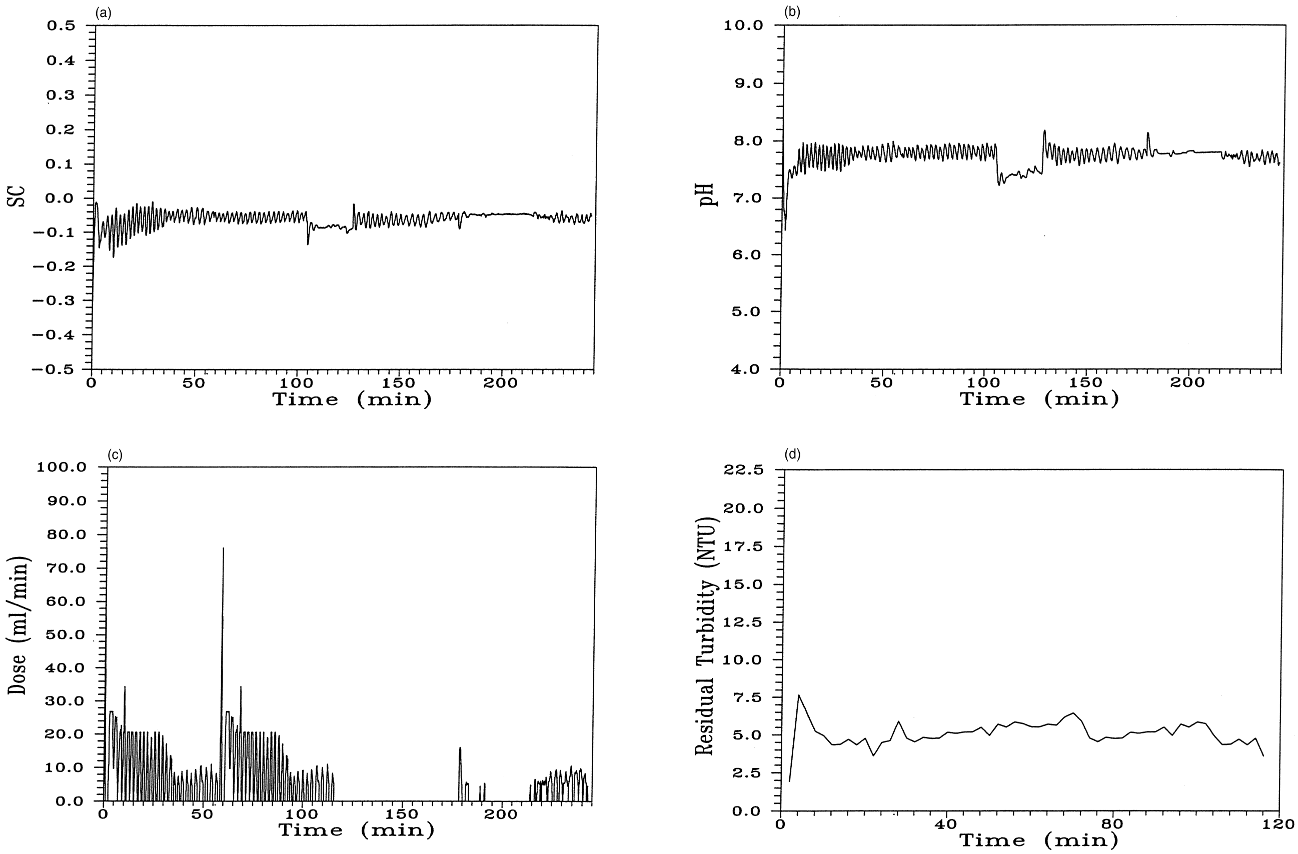

Fig. 2 (a) Streaming current as a function of time during pilot plant operation. Experimental condition: Initial kaolinite concentration = 1000 mg/dm^3, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3. (b) Values of pH as a function of time during pilot plant operation. Experimental condition: Initial kaolinite concentration = 1000 mg/dm^3, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3. (c) Alum dose as a function of time during pilot plant operation. Experimental condition: Initial kaolinite concentration = 1000 mg/dm^3, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3. (d) Residual turbidity as a function of time during pilot plant operation. Experimental condition: Initial kaolinite concentration = 1000 mg/dm^3, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3.

is illustrated in Fig. 2c. The residual turbidity of treated water ranged from 5 to 7 NTU before filtration (Fig. 2d). It is noted that most suspended solids can be effectively removed in the coagulation, flocculation and sedimentation units. The loading on the following rapid sand filter will then be significantly relieved. The water quality could further be improved in the rapid sand filter. Compared with the current National Drinking Water Standard in Taiwan (4 NTU), results from the laboratory-scale plant operation show that the process could perform reasonably well.

Impulse input of ultra-high turbidity water

In Taiwan, several cases of emergency shutdown of water treatment plants have also been reported as a result of the illegal dumping of construction waste in watersheds of creeks and rivers used for public water supply. The intake of raw water with ultra-high turbidity acts as an impulse input of solid load to the water treatment plant. There is little a conventional water treatment plant can do in handling the shock-loading situation. Similar cases of water pollution following road construction have been reported in the UK [19]. In order to evaluate the system under shock-loading circumstances, raw water with an initial turbidity of 798 NTU was spiked with 1 dm^3 of 100 g/dm^3 kaolinite suspension during a steady-state operation. Since the turbidity was not measured in the inlet, the turbidity shock load was not seen on the graphs. However, the suspended solid concentration was estimated at $\approx$ 7.6 g/dm^3. The SC readings fluctuated more significantly (Fig. 3a). A similar perturbation was also found in the pH values (Fig. 3b). Nevertheless, satisfactory treatment efficiencies were still achieved. Except for the peak value of 16 NTU reached after 20 min of operation, the residual turbidity could be decreased to less than 8.5 NTU (Fig. 3d). This showed that the control system responds well to drastic and unexpected changes in raw water quality.

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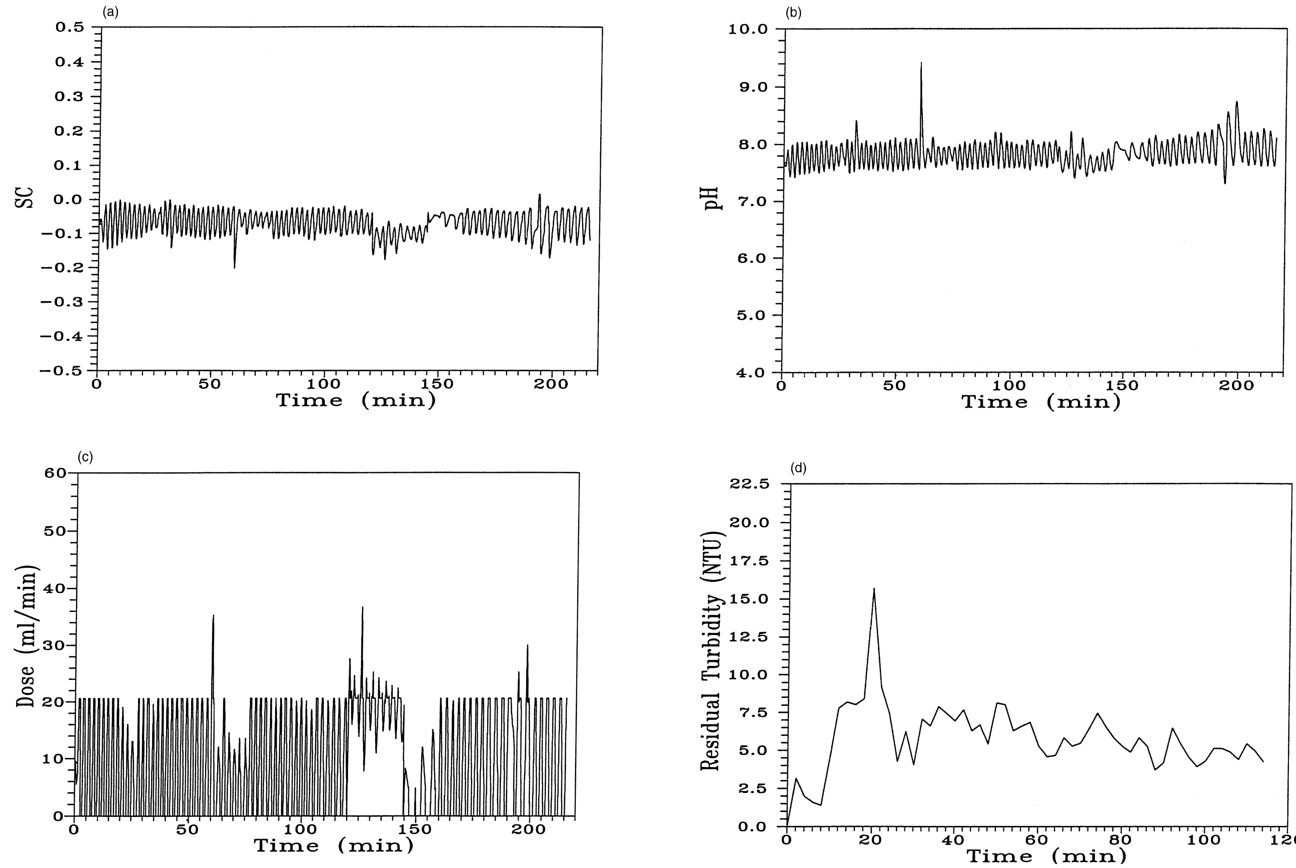

Fig. 3 (a) Streaming current as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 798 NTU, 1 dm^3 of 100 g/dm^3 kaolinite was added, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3. (b) Values of pH as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 798 NTU, 1 dm^3 of 100 g/dm^3 kaolinite was added, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3. (c) Alum dose as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 798 NTU, 1 dm^3 of 100 g/dm^3 kaolinite was added, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3. (d) Residual turbidity as a function of time during pilot plant operation. Experimental condition: Initial turbidity = 798 NTU, 1 dm^3 of 100 g/dm^3 kaolinite was added, I = 0.001 M $NaClO_4$, [$NaHCO_3$] = 100 mg/dm^3.

A comparison between FLC and conventional approaches

Since the essential and most critical step has been noted as coagulation control; i.e. the detection of raw water quality and the determination of coagulant dose, data from qualified jar tests were compiled and some empirical equations were set up to give coagulant dose as a function of raw water turbidity. The following are the empirical equations which were used in the waterworks of Taipei City for determining alum dose (mg/dm^3) when raw water had a turbidity as high as 1000 NTU [1]:

$$[\text{Alum dose}] = 3.0\,[\text{Turbidity}]^{0.5} + 7.0 \ldots \text{upper limit}$$
$$[\text{Alum dose}] = 2.5\,[\text{Turbidity}]^{0.5} + 2.0 \ldots \text{lower limit}$$

These approaches do help to a certain extent. However, in an analysis of the treatment of high-turbidity water in Taipei City, based on operational records and laboratory data from the past 12 years, there are still some cases of highly turbid water during the typhoon season which were deemed untreatable, simply because the conventional dosing approach could not cope [1]. The advantages of the combination of an FLC with a streaming current detector (SCD) are obvious. First, SC monitoring can make the control system totally automatic. This is an improvement on the application of FLC in controlling coagulation reactions in a water treatment plant in Japan [9]. Second, the wide utilisation of SCD in combination with a PID controller has shown some restrictions [7,20,21]. Certain shortcomings have been noted, especially when more than one chemical is added, or when charge-neutralisation is not the governing mechanism of destabilisation [16,18]. An FLC could simultaneously take the pH and surface electrical properties of a colloidal system into account, and provide us with a more flexible response to a given input. Third, the system is shown to respond well to abrupt changes in raw water quality and shock loading conditions. It also has the potential to be applied to the treatment of highly turbid waters that renders sand filters

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inoperative during the monsoon season in tropical countries [4]. In fact, natural and man-made disasters world-wide such as floods, earthquakes and civil unrest can create major disruptions to the infrastructure of a region and in particular may severely damage or overstretch the existing water supply, treatment and distribution systems [22,23]. In addition, damage to or flooding of the sewers can result in highly contaminated water supply systems. The way of ensuring the continuous availability of a sufficient volume of water which is reasonably safe for hygienic and domestic use is a challenge to water treatment engineers and managers [24,25]. Good preparedness has been underlined as the way to respond better during emergencies. We have demonstrated that an automatic controller can equip the water treatment plant better in the face of any unexpected conditions.

Further improvements

Before the system can be scaled up and converted to a real application in water treatment plants, it is recommended that the laboratory-scale system be further improved. Although the system is relatively stable under shock-loading, the alum is dosed in intervals, which can be a disadvantage. The discrete control set-point for SCD may be modified to a fuzzy control set-range, so that the system could become more stable [20]. In addition, since this study was basically a feasibility study, the total alum dose was not recorded. It is still unclear if the FLC system generates a lesser amount of sludge. Besides this, although charge neutralisation is deemed as the major mechanism responsible for a coagulation reaction of highly turbid waters, other mechanisms such as sweep flocculation cannot be completely ruled out. The measurement of alum dose in future work will certainly help our better understanding of coagulation-flocculation reactions. Control rules therefore need to be improved and simplified, taking into account a minimisation of the amount of sludge and the dissolved aluminium concentration. We also need to explore the feasibility of combining an FLC with on-line floc measurement techniques [3,5,26,27]. The present control system could then be transferred into a feed-forward controller. In fact, the self-learning ability of an FLC would make it more versatile. If necessary, adding another input to the FLC, such as floc size, temperature or alkalinity, requires only the addition of another membership function and its associated control rules [15]. Therefore, the fuzzy control system can be modified and adapted to other specific requirements without much difficulty. Finally, since the high concentration of dissolved organic carbon (DOC) is usually found in accompaniment with highly turbid water, the coagulation/flocculation mechanism will then become much more complicated. Further study is also recommended on the performance of the FLC in the presence of DOC.

CONCLUSION

A fuzzy logic controller (FLC) was applied in the automatic control of a coagulation reaction through the continuous monitoring of pH and streaming current. A laboratory-scale water treatment plant, consisting of rapid mixing, flocculation and sedimentation units, was utilised. To simulate conditions of high turbidity in a water reservoir after a typhoon, raw water with turbidity of 600 NTU was tested. It is found that a residual turbidity of lower than 2 NTU could be achieved. The residual turbidity could also be lowered to less than 5–7 NTU of a raw water with ultra-high initial turbidity of 1000 mg/dm^3 of kaolinite. Raw water with an initial turbidity of 798 NTU was spiked with 100 g/dm^3 of kaolinite suspension to evaluate the performance of the system under shock-loading conditions. The fuzzy control system responded satisfactorily, and a residual turbidity of lower than 8.5 NTU was obtained. The current work demonstrates that the SCD is readily incorporated into an FLC. Compared with existing automatic control systems, the advantages of the new design were discussed. Suggestions for further study include modifying the control rules to minimise the residual aluminium concentration and the amount of sludge, and incorporating other instruments for possible feed-forward control.

ACKNOWLEDGEMENTS

The authors are grateful to the National Science Council of Taiwan for the financial support of this work under contract: NSC-84–2621-P-011–001. J. C. L. would like to thank Mr P. J. Buijs and Mr J. T. Groennou for valuable discussions at Kiwa Research and Consultancy, where this manuscript was completed during summer of 1997.

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