Fuzzy model identification and control system design for coagulation chemical dosing of potable water

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Abstract A practical feedforward control system with fuzzy feedback trim is presented for controlling the dosing strategy of Changhsing Water Purification Plant of Taipei Water Department (TWD). The feedforward move is based on a regression model from successful dosing data between 2001 and 2004. The expert operators' adjusting actions in meeting the settled water turbidity trend and pH values are adopted to establish the fuzzy feedback control rules. A host of field tests have demonstrated the effectiveness of the proposed control strategy.

Keywords Chemical dosing; coagulation; feedforward control; fuzzy control

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Introduction

The Changhsing purification plant of Taipei Water Department is responsible for supplying high quality drinking water to more than a million citizens around Taipei city. In order to promote the quality of potable water, many scholars and practitioners have been trying to improve effective management and protection of water resources, purification processing techniques, quality analysis and maintenance of distribution networks (Jiang, 1997; Kang *et al.*, 1999). Less priority is addressed on the systematic study of quality monitoring instrument and automation engineering although these progresses are more in demand by the field operators of the purification plant. When the quality and dosing data are collected and integrated, in addition to on-line automatic dosing control system for prediction and adjustment, then it is expected to come up with in-time most optimum dosing in the changes of coagulant, the high turbidity raw water brought by typhoon and storm water, as well as the faint nuclei water which is difficult to handle. It will help to reduce the probability of operational error and the cost of water treatment chemicals. This paper aims at modelling the human experts' experience and then developing a feedforward and fuzzy feedback control system for the Changhsing plant for supplying high quality drinking water.

Purification processing procedure and water quality monitoring system

The fundamental procedure of a typical purification process includes: (a) coagulation chemical dosing; (b) sedimentation; (c) filtration; and (d) disinfection, which is mainly used to eliminate turbidity and to sterilize, as shown in Figure 1.

Flowchart of coagulation chemical dosing of potable water

A flowchart of coagulating chemical dosing of potable water is shown in Figure 2. We can then characterize the feedforward and feedback control strategies according to control subjects.

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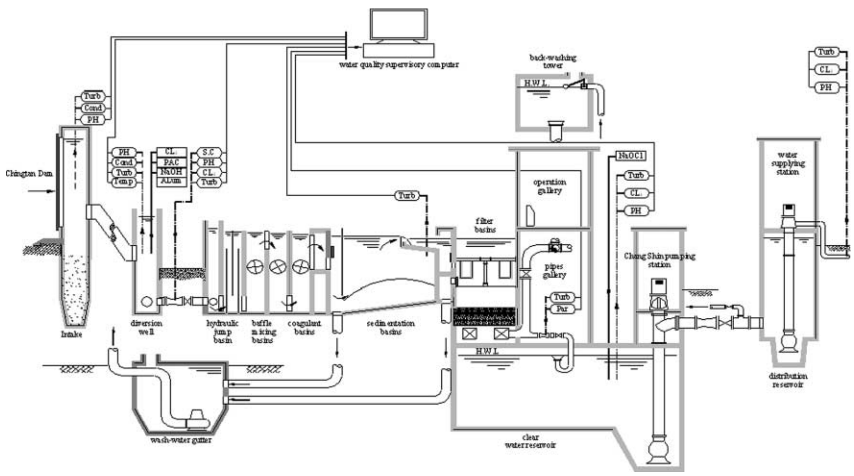

Figure 1 Process flow sheet for Changhsing purification plant

The feedforward control strategy

Chemical coagulation procedure includes chemical dosing, rapid mixing (enabling the coagulant to disperse rapidly and to collide with turbidity particles) and slow mixing (forming coarse floc). During the site operation, the most important issue is to determine a correct dosing formula. However, the dosing patterns prevailing in purification plants are still based on personal experience. Jar tests should be added to obtain the optimal

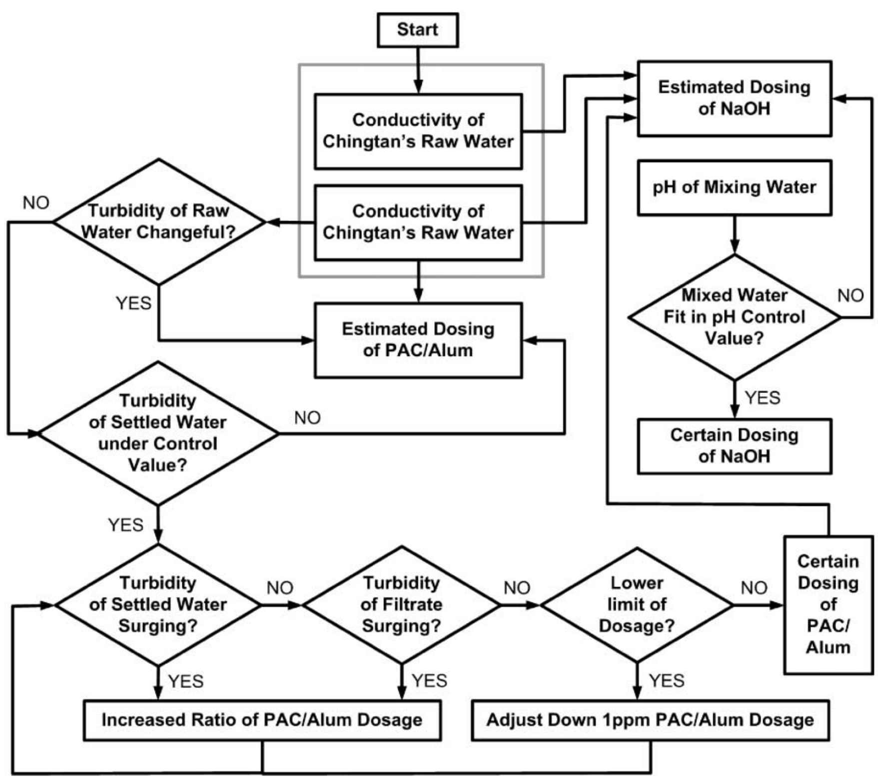

Figure 2 Flowchart of coagulation chemical dosing of potable water

dosing data as the site dosing instruction during the period of abnormal or high turbidity water quality. Particularly, jar test is usually too late to meet practical needs during the raw water quality rapid change period. More often than not to add high level of coagulant would be taken to meet with the sudden situation, and it is easy to cause improper purification quality and extra chemical costs. Furthermore, water treatment is still in step-dosing manipulation to deal with the continuous changing raw water quality, but lacks an effective fine-tuning mechanism. If a continuous adjustment is made in dosing parallel to the changes in turbidity, the precision of dosing control should be able to be improved. Thus, some successful dosing coagulation empirical data are applied to look for the correlation between raw water turbidity and conductivity. Such an empirical dosing quantity will be used as the basis for automatic dosing to arrive at the optimized operation.

Feedforward control with PAC/aluminium sulfate and NaOH coagulant

The successful dosing data of poly aluminium chloride (PAC, containing 10% Al_2O_3 effective component) and the aluminium sulfate (containing 8% Al_2O_3 effective component) of Changhsing purification plant are collected, which includes turbidity and conductivity of raw water, dosing concentration of PAC, aluminium sulfate and NaOH and pH values of water after mixing. Multiple regression of the correlative parameters was conducted using least squares (Penny and Lindfield, 2000). The following polynomials correlate the PAC/aluminium sulfate dosing levels and the turbidity of raw water (Turb) within two nephelometric turbidity unit (NTU) ranges.

$$\mathrm{PAC} = 5.4656 + 0.3529 \times \mathrm{Turb} - 0.00156 \times \mathrm{Turb}^2 + 0.0000023 \times \mathrm{Turb}^3 \quad \text{for } 3\,\mathrm{NTU} < \mathrm{Turb} < 400\,\mathrm{NTU}\ (r^2 = 0.9771) \tag{1}$$

$$\mathrm{PAC} = 27.3535 + 0.0411 \times \mathrm{Turb} \text{ for } 400\,\mathrm{NTU} < \mathrm{Turb} < 1,500\,\mathrm{NTU}\ (r^2 = 0.9973) \tag{2}$$

$$\mathrm{Alum} = 10.0778 + 0.4454 \times \mathrm{Turb} - 0.00165 \times \mathrm{Turb}^2 + 0.0000023 \times \mathrm{Turb}^3 \text{ for } 3\,\mathrm{NTU} < \mathrm{Turb} < 400\,\mathrm{NTU}\ (r^2 = 0.9563) \tag{3}$$

$$\mathrm{Alum} = 33.0788 + 0.0795 \times \mathrm{Turb} \text{ for } 400\,\mathrm{NTU} < \mathrm{Turb} < 1,500\,\mathrm{NTU}\ (r^2 = 0.9709) \tag{4}$$

It is also found that both the conductivity and the pH value of raw water decreased with increasing turbidity and the acid coagulant addition also causes the water quality to be at acidity level. The 45% NaOH is used to adjust the pH value of the mixed water to maintain the optimum coagulation condition. Hence, if PAC is used as coagulant, NaOH non-linear equation can be found, where Cond represents conductivity of raw water:

$$\mathrm{NaOH} = 6.0989 - 0.0866 \times \mathrm{Cond} + 0.0179 \times \mathrm{Turb} + 0.00028 \times \mathrm{Cond}^2 - 0.000007 \times \mathrm{Turb}^2\ (r^2 = 0.9973) \tag{5}$$

Another NaOH non-linear equation can also be found when aluminium sulfate is used as coagulant as shown below, where Alum represents the dosage of aluminium sulfate:

$$\mathrm{NaOH} = -1.4855 + 0.1413 \times \mathrm{Alum} + 0.00321 \times \mathrm{Alum}^2 - 0.00001433 \times \mathrm{Alum}^3\ (r^2 = 0.9973) \tag{6}$$

Control dosing times in conjunction with variations in turbidity of raw water

The main disturbances of the feedforward control action include distant Chingtan raw water turbidity and conductivity. When detecting the raw water turbidity and conductivity of Chingtan, the dosing adjustment in Changhsing diversion well will occur 90 minutes later. Nevertheless, the dosing timing should be adjusted according to the trend of raw water turbidity due to the influence of fluid flowing and mass transfer diffusion in the process of water transportation. The adjusting time should be advanced to 80 minutes later in Changhsing diversion well when the turbidity of raw water in Chingtan weir is on an upward trend. The adjustment needs to be delayed to be 100 minutes later if the raw water turbidity is on the downward trend. This experience can be expressed verbally as:

$$R1 : \text{IF}\, S_1 > 0\, \text{THEN Dos. time is}\, 90 - 10 = 80\, \text{min}\, s$$

$$R2 : \text{IF}\, S_1 < 0\, \text{THEN Dos. time is}\, 90 + 10 = 100\, \text{min}\, s$$

$$S_1 = \frac{\text{raw water turbidity}(t) - \text{raw water turbidity}(t-1)}{\Delta t}$$

Feedback control strategy

Apply settled water turbidity to perform feedback control (I)

Under different turbidity ranges of raw water, the average turbidity of various settling pond water of Changhsing purification plant is used as the controlled variable to perform the automatic adjustment of dosage regression equation multipliers. The results of jar tests are also applied for manual adjustment of the multiplier of dosage regression equation. The feedback control adjustment is performed every 100 minutes (90 minutes after dosing and 10 minutes for averaging the turbidity of various settling pond water).

Based on the average of turbidity of settling pond water calculated from different raw water turbidity ranges applying PAC and aluminium sulfate coagulants, respectively, some conditional descriptive statements can be inferred to express fuzzy control rules:

$$R3 : \text{IF}\, S_1 \neq 0\, \text{and}\, X_{\text{ij}} > A_{\text{ij}}\, \text{THEN change Dos. Time} = 100\, \text{min and}\, D(t) = B_1 D(t - 100)$$

$$S_1 = \frac{\text{raw water turbidity}(t) - \text{raw water turbidity}(t-1)}{\Delta t}$$

where S_1 is the slope of raw water turbidity; i denotes the raw water turbidity of different range; j represents settling pond water of different units; X_{ij} is turbidity of settling pond water in actual raw water turbidity range (NTU); A_{ij} is turbidity of settling pond water in different turbidity range of raw water (NTU); $D(t)$ and $D(t-100)$ are timely dosage and dosage 100 minutes ago (ppm), and B_1 is a multiplier of 1.1 times of dosage regression value.

Cope with surging turbidity of settled water and automatically reduce dosage to perform feedback control (II)

Affected by season, temperature, algae, microbes and outside pollutants, raw water quality is capricious all the time. Under the same turbidity the chemical and physical characteristics of colloid are not always the same. It is unavoidable to deal with a lot of emergency in the water treatment. In statistically processing the operation and control strategies of dosing related to the surge of turbidity of settled water, a fuzzy control mode can be established.

Input verbal variable — scaled rate of change X = {SS, S, M, L}. Where “SS”, “S”, “M”, and “L” represent slightly, light, medium and large, respectively, upward trends of turbidity of settled water. The membership functions of scales rate of change are shown in Figure 3.

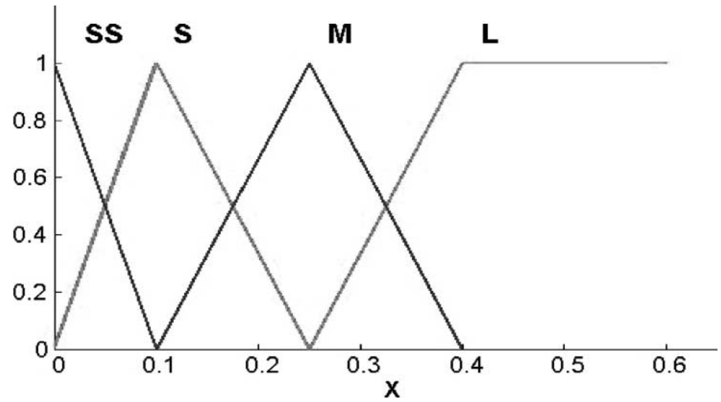

Figure 3 The membership function of scaled rate of change

Output verbal variable — increased ratio of dosage $Y = \{Z, S, M\}$. Where: "Z" represents nil adjustment of dosage; "S" represents slight adjustment of dosage; and "M" represents large adjustment of dosage, respectively. The specific singletons are used as output operation intensities. The membership functions of increased ratio of dosage are shown in Figure 4.

Establishing fuzzy control rule base with the operation and control experience of turbidity surge of settled water.

$$\text{Rule 1}: \text{IF } X \text{ is } SS \text{ THEN } Y = Y_1 = Y_Z = 0$$
$$\text{Rule 2}: \text{IF } X \text{ is } S \text{ THEN } Y = Y_2 = Y_S = 0.2$$
$$\text{Rule 3}: \text{IF } X \text{ is } M \text{ THEN } Y = Y_3 = Y_S = 0.2$$
$$\text{Rule 4}: \text{IF } X \text{ is } L \text{ THEN } Y = Y_4 = Y_M = 0.4$$

The increased ratio of dosage can be obtained from the weighted average (Sun and Yang, 1994).

$$Y = \frac{\sum_i \phi_i(X) Y_i}{\sum_i \phi_i(X)} = \sum_i \phi_i(X) Y_i \quad = \begin{cases} \phi_{SS}(X) Y_Z + \phi_S(X) Y_S; & \text{if } 0 \le X < 0.1 \\ \phi_S(X) Y_S + \phi_M(X) Y_S; & \text{if } 0.1 \le X < 0.25 \\ \phi_M(X) Y_S + \phi_L(X) Y_M; & \text{if } 0.25 \le X < 0.4 \\ \phi_L(X) Y_M; & \text{if } 0.4 \le X \end{cases}$$

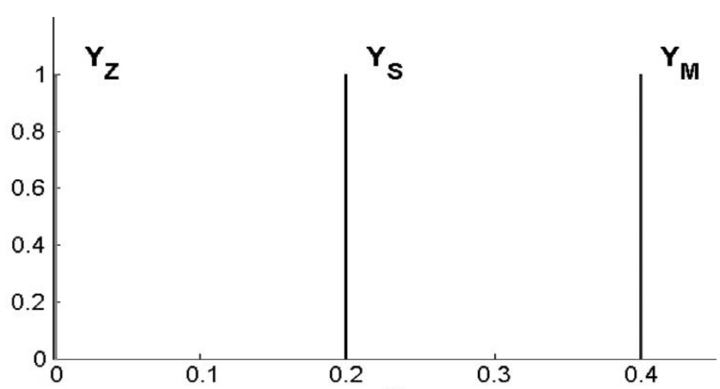

Figure 4 The membership function of increased ratio of dosage

Meanwhile, during the period of low turbidity and stable raw water quality, operators tend to keep the dosage unchanged when the water output is just as the well condition. We experimented during a low turbidity of raw water (about 10NTU), to decrease dosage from 7 ppm of PAC to 6 ppm, and then to descend to 5 ppm. The water turbidity held steady at 1.2 NTU. In this research we are trying to establish "searching for optimum dosing mechanism" by gradually reducing the dosage under automatic control manner while the output water quality is maintained in a good condition, so as to attain the goal of reducing the aluminium salt content in output water and the cost of water treatment.

This research adopted a trial and error approach to perform the optimum dosing chain rule, but the output of dosage is not supposed to exceed the upper and lower limit of dosage. The fuzzy control rules are shown in the following:

$$R4: \text{IF } S_1 \approx 0 \text{ and } S_2 \leq 0 \text{ THEN change Dos. Time} = 100 \min s \text{ and } D_2(t) = D_2(t-100) - 1 \text{ and } D(t) \geq D_{\min}$$

$$R5: \text{IF } S_1 \approx 0 \text{ and } S_2 > 0 \text{ THEN change Dos. Time} = 100 \min \text{ and } D_2(t) = (1+Y)D_2(t-100) \text{ and } D(t) \leq D_{\max}$$

where

$$S_1 = \frac{\text{raw water turbidity}(t) - \text{raw water turbidity}(t-1)}{\Delta t}, \text{turbidity slope of raw water}$$

$$S_2 = \frac{\text{settled water turbidity}(t) - \text{settled water turbidity}(t-1)}{\Delta t}, \text{ turbidity slope of settled water}$$

$D_2(t)$ is the in-time dosage (ppm) at Changhsing diversion well; $D(t)$ is total dosage output; $D_{\max}$ and $D_{\min}$ are upper and lower limits of dosage.

Limitation of maximum and minimum dosages

In order to avoid the dosing deviation of dosing automatic control due to system and detector abnormality, an upper and lower dosage limit control is imposed to guide the feedback control operation adjusted within a safe range, where $D_R(t)$ represents regression concentration of dosage (ppm), B_2 and B_3 are multipliers of 0.8 and 1.4, respectively.

$$R6: D_{\min} = B_2 D_R(t)$$
$$R7: D_{\max} = B_3 D_R(t)$$

Mixed water pH feedback control (III)

Coagulant dosing must be controlled at the most suitable pH value to flocculate. Except for the approximate dosing of NaOH by the feedforward system, it also needs to measure the pH value of mixed water to adjust the dosage of NaOH.

Establishing a fuzzy control rule base for target pH value by applying PAC/aluminium sulfate coagulant. The pH control experience of mixed water with PAC coagulant is analyzed, and the relationship of turbidity of raw water to pH distribution of mix water can be induced.

1. Turbidity of raw water at 300 and 1,500 NTU, pH value should be maintained at 6.9
2. Turbidity of raw water at between 120 and 299 NTU, pH should be 7.0
3. Turbidity of raw water at under 119 NTU, pH should stay above 7.1

Use raw water turbidity as the measuring variable and target pH value as operating variable, the control knowledge base can be designed as below. "L", "M" and "H" represent low, medium and high raw water turbidity phases, respectively, for input verbal variable X, the raw water turbidity; "H", "M" and "L" represent settings at high, medium and low pH values, respectively, for output verbal variable Y, the target pH value. Here, some specific singletons are adopted as the output operating intensity:

$$\text{Rule 1}: \text{IF } X \text{ is L THEN } Y = Y_1 = Y_H = 7.1$$
$$\text{Rule 2}: \text{IF } X \text{ is M THEN } Y = Y_2 = Y_M = 7.0$$
$$\text{Rule 3}: \text{IF } X \text{ is H THEN } Y = Y_3 = Y_L = 6.9$$

Target pH value can be derived from the following weighted average approach:

$$Y = \frac{\sum_i \phi_i(X) Y_i}{\sum_i \phi_i(X)} = \sum_i \phi_i(X) Y_i \quad = \begin{cases} \phi_H(X) Y_L + \phi_M(X) Y_M; & \text{if } 300 \leq X \leq 1,500 \\ \phi_M(X) Y_M + \phi_L(X) Y_H; & \text{if } 120 \leq X < 299 \\ \phi_L(X) Y_H; & \text{if } 0 \leq X < 119 \end{cases}$$

Establishing fuzzy conditions and rules for NaOH dosing. As the detected pH is very nimble, the pH feedback control system will establish NaOH dosing fuzzy control conditional rules through every 10 minutes adjustment of NaOH dosing,

$$R8: \text{IF pH} > \text{Y THEN change Dos. Time} = 10\,\text{min}\,s \text{ and NaOH DOS.}(t) = \text{NaOH DOS.}(t-10) - 1$$
$$R9: \text{IF pH} < \text{Y THEN change Dos. Time} = 10\,\text{min}\,s \text{ and NaOH DOS.}(t) = \text{NaOH DOS.}(t-10) + 1$$

Field operation verification

The field dosing operation at Changhsing purification plant during 2003 and 2004 has applied the regression values of coagulants and NaOH as the basis for dosing operation and the results of treatment are substantially conformed to expectation. The following are two cases of field operations.

Case 1. On 10 January 2005, when the raw water turbidity is maintained at 5 NTU, PAC dosage reduced from 9 ppm to 7.5 ppm and decreased further to 6.5 ppm. The dosing range is not deviating from the upper/lower limit of dosing at PAC regression value 7.19 while raw water turbidity is at 5 NTU. The turbidity of settled water was maintained at 1.5 NTU, and the turbidities of settling pond water were also lower than the control value. pH of mixed water was maintained at 7.1–7.4, which conformed to the target value set in pH control rule base. It is verified that when the turbidity of raw water is stable, the automatic dosing reduction strategy between upper and lower limits of dosage is indeed feasible.

Case 2. On 7 February 2005 at 4 pm the turbidity of raw water rose from 5 to 7.7 NTU and PAC dosage maintained at 6.3 ppm. The upper and lower limits of dosing of raw water turbidity 5 NTU PAC dosing regression value 7.2 ppm and raw water turbidity 7.7 NTU PAC dosing regression value 8.1 ppm, and settled water turbidity rose from 1.0 NTU to 1.7 NTU. While the turbidity of settled water is lower than the control values, if dosing is adjusted upward following the increase trend of raw water turbidity, it will not occur with turbidity peak of settled water. If the regression equation is applied to adjust dosage to cope with the change in turbidity, it will help to stabilize the quality of water output. Meantime, during the period of 07:30–11:30 pm, raw water turbidity was maintained at 6 NTU. From the rise of turbidity of settled water, it is derived that scaled rate of change = 0.24 at 8:30 pm, PAC dosage increases from 6.3 ppm to 7.5 ppm with an increase of dosing ratio about 0.2. It conformed to the control rule of feedback control (II). After process reaction, the turbidity of settled water dropped from 1.3 NTU to 1.0 NTU. This also proved that at the surge of settled water and filtrate, applying operation and control strategies to reduce the turbidity of settled water and filtrate can improve treatment of abnormal water quality. As well as mixed water pH at 7.2–7.4 is not deviating from the target pH value set.

Conclusion

The water purification is a complicated time-varying system which gives rise to uncertainty, urgency and safety considerations. In this research, the statistical result of empirical operation was applied to form the feedforward control strategy with feedback trim. By completely realizing the dosing control actions of human domain experts, the proposed fuzzy control method can help minimizing field operators' errors in water purification operation. A host of field tests have demonstrated the effectiveness of the proposed control strategy.

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