Development of automatic coagulant dosage control technology for rapid change of raw water quality parameters

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ABSTRACT

An automatic coagulant dosage control technology for water purification plants was developed to deal with rapid changes of raw water quality parameters. Control logic was developed to decide coagulant dosage based on aluminum concentration in rapid mixing tank water based on results of semi-pilot scale experiments. This logic enabled quick feedback on the excess or lack of coagulant. It was found that the aluminum residual rate, which was proposed as an indicator of coagulation reactions, could be given as a function of coagulant dosage and turbidity. The effectiveness of the control logic was verified in semi-pilot scale experiments. Settled water turbidity was within ±0.5 NTU of target value even when raw water turbidity increased rapidly up to 100 NTU.

Key words | aluminum, automatic control technology, coagulation–sedimentation process, small flocs

INTRODUCTION

In Japanese water purification plants, coagulation–sedimentation process is commonly used for surface water. Generally, this process is controlled by feedback (FB) control based on settled water turbidity. When raw water quality parameters change rapidly due to heavy rains for example, there is a possibility that settled water turbidity exceeds a target value because of the delay originating from retention time of the sedimentation tank. This has an undesirable influence on the subsequent sand filtration process. In such cases, a coagulant dosage is adjusted manually by expert operators, many of whom are expected to retire in a few years. Therefore, automatic control technology is required that can do what experts now do. Several groups have studied methods to deal with the sudden change of raw water quality parameters (Annadurai et al. 2004; Lin et al. 2005). A method to increase coagulant dosage with these values measured before normal raw water quality parameters measurement was suggested. However, it tends to inject surplus coagulant. In the case of using an aluminum (Al) component coagulant such as poly aluminum chloride (PACl), this means an increase of Al concentration in tap water. It becomes the cause that the high Al concentration increases chromaticity of the water. Therefore a technique to shorten the delay time for FB control should be considered. To make an early judgment about coagulation dosage, a coagulant dosage control method using growth start time of flocs was proposed (Yamaguchi et al. 2010). The electric potential value that is near the zeta electric potential can be measured by a streaming current detector (Dentel et al. 1989a, b; Maeda et al. 2005; Xia et al. 2007), or laser light scattering (Watanabe et al. 2005; Gregory 2009).

In this study, improved FB control was used for coagulant dosage control. In order to shorten the delay time, an indicator based on Al concentration of water in the rapid mixing tank was developed. Al, mostly in the form of PACl, is commonly used as a coagulant in Japanese water purification plants. It was supposed that judgment of
coagulant excess or lack was possible using Al concentration (Yokoi et al. 2009). The new coagulant dosage control logic based on Al concentration measurements of water in the rapid mixing tank was evaluated.

**EXPERIMENTAL**

**Coagulant dosage control system**

Figure 1 is a flow diagram of the new coagulant dosage control system. This system is mainly comprised of a coagulant feeding facility, a flocs classification system, an Al concentration measuring system, coagulant dosage operational equipment, and equipment for water analysis (turbidity, chromaticity, pH, alkalinity, water temperature). The coagulant dosage is decided from feedforward (FF) control and the FB control. In the presented system, the value (PACl₀) for the FF control is calculated from two raw water quality parameters (raw water turbidity, water temperature). The value (ΔPACl) of the FB control is calculated from differences between the Al residual rate (ARR) and its target value. Here, residual Al specifically refers to the sum of the concentration of Al present in small flocs, and in dissolved form in the water of the rapid mixing tank. The rate of this Al concentration to that of the dosed coagulant is denoted as ARR. The ARR is divided by the residual Al concentration in the coagulant dosage, and it is associated with the coagulation state by the jar test (Yokoi et al. 2009). In a conventional system, the value of the FB control is calculated from differences between settled water turbidity and its target value. The developed system differs from the conventional system regarding the sampling point of water for FB control and the water quality to be measured.

In this study, the coagulant dosage control system was implemented on a semi-pilot scale coagulation–sedimentation process apparatus. A coagulant dosage control experiment was carried out with conditions that simulated a rapid change of raw water quality parameters such as due to heavy rain. At typical purification plants, the tolerance level of settled water turbidity is around ±0.5 NTU for the target value. Therefore this experiment assumed turbidity change was within ±0.5 NTU. Before confirmation of the control effect by the developed system, the ARR calculation formula and coefficients of each control expression were decided. The results obtained with the new system were compared with those of the conventional system to assess its effectiveness.

**Experimental apparatus**

Figure 2 shows specifications and setup of the coagulation–sedimentation process apparatus for the coagulant dosage control experiment. The main components were the rapid mixing tank (capacity 10 L, residence time 5 min), the floculator (120 L, 60 min), the sedimentation tank (280 L, 140 min), the flocs classification system, and the Al concentration measuring system. There were two setups (setup 1 and 2); only setup 1 had the flocs classification system and the Al concentration measuring system.
PACl coagulant was injected into the raw water in the rapid mixing tank. In the flocculator, the water from the rapid mixing tank was slowly stirred to promote floc growth. The flocculated water was transferred to the sedimentation tank. In the sedimentation tank, the flocs settled out and the settled water flowed to an outlet port. Part of the rapid mixing tank water was supplied to the floccs classification system and flocs were classified. When mixing water includes a large quantity of suspended matter and coagulant, Al concentration measurement is difficult. In addition, judgment accuracy of coagulant excess and lack is raised by choosing small flocs which are the last to settle. Therefore, processing water classified as being rich in small flocs was supplied to the Al concentration measuring system and the residual Al concentration was measured. Experimental conditions of the coagulation–sedimentation process apparatus were set by referring to Japanese water service facility design indicators (JWWA 2000; JSCE 2004). The apparatus was operated automatically to control coagulant dosage from raw water turbidity, water temperature, residual Al concentration, and settled water turbidity.

Figure 3 is a schematic diagram of the flocs classification system. This system used a cylindrical rotating strainer (SUS316) for floc filtration. The strainer was rotated to realize effective cross flow filtration, and controlled confinement. When the coagulation processing is appropriate, the number of initial microparticles decreases and particles in the raw water can be processed at high efficiency by filtration (Ebie et al. 2007). If coagulation processing is poor, there will be many small flocs (particle sizes less than 10 μm), so a 10 μm particle filter was used in this study. Because raw water turbidity was high in this experiment, prevention of occlusions was judged to be insufficient only in the cross flow filtration. Therefore, the filter was ultrasonically cleaned on a regular basis.

To measure residual Al concentration by absorption spectrophotometry (at a wavelength of 535 nm), Eriochrome Cyanine R (ECR) reagent and acetic acid buffer solution (pH 5.0) were used. A predetermined amount of the ECR reagent (Merck, Ltd) was dissolved in pure water and the ECR solution pH was adjusted to 1.9 using hydrochloric acid. This pH was chosen to prevent deterioration of the ECR reagent and to dissolve Al present in the small
flocs. The Al concentration was calculated from absorbance. A standard curve (0–0.3 mg/L, R = 0.99) used for concentration calculation was made by using Al standard solution (AlK(SO₄)₂, Wako Pure Chemical Industries, Ltd).

**Automatic coagulant dosage control logic**

**Feedforward control and feedback control**

Control logic of the developed system was used in combination with FF control to calculate a basic coagulant dosage based on raw water quality parameters and with FB control to calculate a corrected value. This was described by Equation (1).

\[
PACl(t) = PACl_0(t) + \Delta PACl(t) \quad (1)
\]

Here \(PACl(t)\) is coagulant dosage at time \(t\) [mg/L], \(PACl_0(t)\) is basic coagulant dosage at time \(t\) [mg/L], \(t\) is time [min], and \(\Delta PACl(t)\) is the corrected value at time \(t\) [mg/L].

The FF control for \(PACl_0(t)\) was given by Equation (2) which is an empirical formula based on actual experimental data.

\[
PACl_0(t) = C_1 \times T_0(t)^k \times T_0(t)^1 \quad (2)
\]

Here \(C_1\), \(k\) and \(l\) are coefficients, \(T_0(t)\) is \(T_1(t)\)–273 at time \(t\) [K], \(T_1(t)\) is water temperature at time \(t\) [K], and \(T_0(t)\) is raw water turbidity [NTU]. Coefficients of Equation (2) were obtained from results of a coagulant dosage constant experiment.

The FB control for \(\Delta PACl(t)\) used PI control consisting of proportionality and integral terms as shown in Equation (3).

\[
\Delta PACl(t) = C_2 \times (R_{Al}(t) - R_{Alc}(t)) \times PACl(t - \tau) + C_3 \\
\times \Delta PACl(t - \tau) \quad (3)
\]

\[
R_{Al}(t) = (Al_1(t)/Al_0(t)) \times 100 \quad (4)
\]

Here, \(Al_0(t)\) is Al concentration of time \(t\) converted from coagulant dosage [mg/L], \(Al_1(t)\) is residual Al concentration at time \(t\) [mg/L], and \(C_2\), \(C_3\) are coefficients. \(PACl(t-\tau)\) is coagulant dosage 1 control period before time \(t\) [mg/L], \(R_{Al}(t)\) is ARR at time \(t\) [%], \(R_{Alc}(t)\) is the target value of ARR at time \(t\) [%], \(\Delta PACl(t)\) is the corrected value at time \(t\) [mg/L], \(\Delta PACl(t-\tau)\) is the corrected value 1 control period before time \(t\) [mg/L], and \(\tau\) is the time period duration [min]. Equation (3) was based on an expression implemented by the monitoring control system of a purification plant. \(PACl(t-\tau)\) is multiplied by a factor in Equation (3) so that rate of correction changes with the excess and lack of coagulant dosage. In addition, \(Al_0(t)\) was used as a measured value for the first 5 min in consideration of the delay time from the rapid mixing tank to the Al concentration measuring system. The values of \(C_2\) and \(C_3\) were 0.015 and 1.0, and the time period duration was 1 min.

The FB control for the conventional system used Equation (5) which has been implemented in a purification plant.

\[
\Delta PACl(t) = C_4 \times (Tu_s(t) - Tu_t) \times PACl(t - \tau) + \Delta PACl(t - \tau) \quad (5)
\]

Here \(C_4\) is a coefficient, \(Tu_s(t)\) is settled water turbidity at time \(t\) [NTU], and \(Tu_t\) is the target value of settled water turbidity [NTU]. \(C_4\) was 0.005 in consideration of the speed of an overshoot and reply (Yamamoto & Kato 1997). The time period duration was 10 min.

**Target value of ARR calculation formula**

ARR is associated with settled water turbidity (Yokoi et al. 2009). However, the relationship between ARR and turbidity in classification processing water is different from that in settled water. Therefore, the target value of the ARR calculation formula was structured from a coagulant dosage constant experiment.

**Method**

**Simulated raw water**

Simulated raw water with turbidity was prepared by adding highly-concentrated kaolin (5,000 NTU, Wako Pure Chemical Industries, Ltd) to tap water. PACl (Al₂O₃ density:
10 wt. %) was used as the coagulant and it was supplied to the rapid mixing tank after dilution by 100 times. This is because there are many water purification plants using PACI in Japan. In addition, because the ultraviolet absorbance increases and decreases just as turbidity in raw water of an actual river, humic acid solution was added to the simulated raw water. The humic acid solution was prepared by dissolving humic acid reagent (Wako Pure Chemical Industries, Ltd) in an alkali solution and filtering.

Coagulant dosage constant experiment

Table 1 lists experimental conditions for the coagulant dosage constant experiment. To decide coefficients of the FF logic equation, the coagulation–sedimentation process apparatus was operated until settled water turbidity became constant (4–12 h, setup 1). Raw water quality parameters and coagulant dosage were kept constant. The raw water flow rate was 2.0 L/min. Water temperature and settled water turbidity were measured. The coefficients of Equation (2), $C_1$, $k$, $l$, were obtained from the data set.

The apparatus was operated for more than 1 hour to obtain the target value of the ARR calculation formula. Raw water quality parameters and coagulant dosage were kept constant. Water from the rapid mixing tank was supplied to the flocs classification system, and the flocs were classified (number of rotations of the rotating strainer: 100 rpm). After waiting at least 15 min, the classification processing water quality became constant and the stable value of the residual Al concentration was measured in the Al concentration measuring system. Experimental conditions were the same as in Table 1, and the raw water flow rate was 2.0 L/min.

Coagulant dosage control experiment

Figure 4 plots raw water quality parameters in the coagulant dosage control experiment. It was set in reference to raw water quality parameters of an actual purification plant. Even if this case has decreased alkalinity following a storm, the coagulation performance of PACI assumes a kept case by alkaline agent infusion. The initial raw water turbidity was 30 NTU, and the maximum value was 100 NTU. The initial ultraviolet absorbance value was 0.05 cm⁻¹, and the maximum value was 0.25 cm⁻¹. It has been reported that 84% of purification plants with a mean throughput of more than 30,000 m³/d using surface water have a maximum turbidity of less than 100 NTU (JWWA 2008). Therefore, it was judged from this experiment that the developed system would be applicable to 84% of all purification plants.

At first in the coagulant dosage control experiment, settled water turbidity was allowed to arrive at a steady value after the raw water quality became constant. Then, raw water quality parameters changed rapidly. Then, residual Al concentration, ARR, corrected value, coagulant dosage, and settled water turbidity was measured. Target value of settled water turbidity was 1.0 NTU. The aim of this experiment assumed the turbidity change was within ±0.5 mg/L when the raw water flow rate was 2.0 L/min and rotation number of the rotating strainer was 300 rpm.

RESULTS AND DISCUSSION

Coagulant dosage constant experiment

Deciding the target value of the ARR calculation formula

Figure 5 plots relationships among settled water turbidity, coagulant dosage, residual Al concentration, and ARR. For the rapid mixing tank water, the amount of Al was directly proportional to the increase of coagulant dosage. However, when coagulant dosage increased, it was easy for suspended matter to agglomerate, and the amount of small flocs included in the classification processing water decreased. Therefore residual Al concentration decreased with the increase of coagulant dosage. Also, ARR decreased with
an increase of coagulant dosage. In addition, the influence of coagulation dosage on ARR was bigger than that of residual Al concentration. In addition, ARR increased with an increase of settled water turbidity. It was hard for suspended matter to agglomerate so that coagulant dosage was low, and this meant that the quantity of small flocs included in settled water increased. Also, ARR for the same settled water turbidity decreased with increase of raw water turbidity. This phenomenon was different from that seen in the jars test. In the jars test, settled water turbidity and ARR correlate without any dependence on raw water turbidity (Yokoi et al. 2009). It was thought that the floc growth of the coagulation–sedimentation mechanism influenced raw water turbidity in the present experiment. Floc growth is caused by collisions between particles, and it is influenced by the number of particles. In other words, floc growth becomes easy when there are many flocs and other suspended matter present. Therefore raw water turbidity becomes a factor affecting floc growth rate. In the case of the jars test, residual Al concentration is not affected by the floc growth rate. This is because the size of the flocs becomes saturated for a long floc growth time. However, in the experiment, floc growth time was short and floc growth was insufficient. It was thought that residual Al concentration was affected by floc growth rate. As a result, the target value of ARR was found as a function of raw water turbidity and settled water turbidity, and the ARR calculation formula is as follows:

$$R_{Al}(t) = C_3 \times T_{0}(t)^{m} \times T_{m}^{n}$$  \hspace{1cm} (6)

Results of Equation (6) accorded well with experimental values. When experimental conditions of the coagulation–sedimentation process apparatus, flocs classification system and/or the Al concentration measuring system were changed, it was necessary to change the coefficients of Equation (6). This coefficient tuning was done before the coagulant dosage control experiment.
Coefficient determination of FF formula

In the coagulant dosage control experiment, the target value of settled water turbidity was 1.0 mg/L. Therefore, coefficients were decided using 18 sets of data in which settled water turbidity was around 1.0 mg/L. As a result of least square fitting, the coefficients of the FF formula, Equation (2), were obtained as $C_1 = 7.0$, $k = 0.60$, $l = -0.28$.

Coagulant dosage control experiment

Figure 6 shows results of the coagulant dosage control experiment. Raw water conditions were: temperature $284 \pm 1$ K; pH $7.5 \pm 0.1$; alkalinity $32 \pm 2$ mg-CaCO$_3$/L. Residual Al concentration reached 0.199 mg/L 1 h after the experiment started (initial Al concentration, 0.141 mg/L), and it reached 0.165 mg/L 5.0 h after the start. Rapid increase of residual Al concentration occurred because the number of small flocs in mixing water increased. The ARR exceeded the target value from the start of the experiment to 0.5 h. This was because residual Al concentration increased rapidly. Then the rate followed the target value afterwards. ARR fell to 4.7% at 1.0 h, and finally increased to 7.4%. Corrected value of the developed system reached 25 mg/L after 1.0 h, and fell to 15 mg/L 5.0 h after the start. Coagulant dosage reached 80 mg/L, and fell to 42 mg/L 5.0 h after the start. Compared to the conventional system, the developed system had excess coagulant dosage of 20 mg/L when the raw water turbidity and ultraviolet absorbance had their peak values. It was determined that the corrected value based on the ARR was appropriate. Settled water turbidity increased after 1.5 h and reached 1.25 NTU (target value $+0.25$ NTU). It finally fell to 0.78 NTU.

Settled water turbidity in the developed system could be maintained at the target value of 1 $\pm$ 0.3 NTU, and good control was possible. In contrast, the corrected value of the conventional system started to increase after 2.0 h, and there was some delay time. As a result, the settled water turbidity reached 2.25 NTU in the conventional system, indicating poor control. As observed above, the effectiveness of the developed system was confirmed from comparison with the conventional system.

The determination of appropriate coagulant dosage calls for the experience and know-how of expert operators. However, there are high training costs for operators because experience and know-how are not accumulated immediately. A developed system resolves the issue of mass retirement of expert operators in the near future. In addition, although the settled water turbidity target was $\pm 1.3$ NTU, the developed system was able to get a target value of $\pm 0.5$ NTU. So the load quantity to sand filters will be reduced, and the purification plants will still be maintained appropriately.

CONCLUSIONS

An automatic coagulant dosage control technology for water purification plants was developed to deal with rapid changes of raw water quality parameters. From semi-pilot scale experiments, control logic to the determined coagulant dosage based on Al concentration in the rapid mixing tank.
water was developed. This logic enabled quick feedback regarding excess or lack of coagulant. It was found that the ARR, which was proposed as an indicator of coagulation reactions, could be given as a function of coagulant dosage and turbidity. Effectiveness of the control logic was verified. Settled water turbidity was within ±0.5 NTU of the target value even when raw water turbidity was increased rapidly to 100 NTU. This result suggested that a developed system would provide automatic operation of the coagulation–sedimentation process without the action of expert operators even for rapid changes of raw water quality parameters.

REFERENCES


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