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# Decreasing residual aluminum level in drinking water①

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**Abstract:** The relativity of coagulant dosage, residual turbidity, temperature, pH etc. with residual aluminum concentration were investigated, and several important conclusions were achieved. Firstly, dosage of alum-coagulant or PACl influences residual aluminum concentration greatly. There is an optimal-dosage-to-aluminum, a bit less than the optimal-dosage-to-turbidity. Secondly, it proposes that decreasing residual aluminum concentration can be theoretically divided into two methods, either decreasing (even removing) the concentration of particulate aluminum component, or decreasing dissolved aluminum. In these tests there is an optimal value of residual turbidity of post-precipitation at 7.0 NTU. Thirdly, residual aluminum level will increase while water temperature goes higher. At the last, optimal pH value corresponds a minimum dissolved aluminum at a given turbidity. Data shows the optimal pH value decreases with water temperature's increasing.

**Key words:** drinking water; water treatment; residual aluminum; pH

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## 1 INTRODUCTION

Although aluminum is one of the most common metals in our lives, medical researches have proved that aluminum intake in the body will do a lot of harm to human's health. In an effort to control aluminum concentration in drinking water many countries and health organizations have established strict guidelines[1-5]. In China, a guideline level of 0.2 mg/L for aluminum in drinking water was first proposed in "the technique developmental project for municipal water supply in 2000" which is issued by Chinese Construction Department. It was not until 2001 that a guideline level of 0.2 mg/L for aluminum was established in Health Standard for Drinking Water of China[6].

Nowadays, China is confronting a serious situation of aluminum concentration in drinking water. There are a few causes. Alum or polyaluminum chloride (PACl) coagulant is commonly used in most water treatment plants, and occurring technical drawbacks result in high dosage of coagulants, and so, high residual aluminum concentration. The average of current residual turbidity is as high as 3 NTU in treated water.

A recent investigation of drinking water quality conducted in 40 cities in China illustrates that 32.5% of the cities can't conform to 0.2 mg/L aluminum guideline, while in the northeastern cities alone there are 76.9%[7, 8]. Furthermore, the level of 0.2 mg/L is much higher than that of 0.05 mg/L, which is set up by EEC and many other developed countries as well as US.

Therefore, according to the water source quality and its new standard in China, management strategies to minimize aluminum in drinking water require improvement and more testing. Our research is to study how to define the optimum hydraulic and chemical conditions in water treatment plants, and how to choose proper technical parameters in order to decrease aluminum concentration in drinking water efficiently.

## 2 EXPERIMENTAL

### 2.1 Laboratory test

Some 1-letre-beaker tests were designed. The influences of PACl coagulant dosage, water temperature, pH and residual turbidity on residual aluminum concentration in treated water were studied[9].

In order to achieve needed stable turbidity of raw water, authors adopted a man-made substitute which was mixed by some clean deep-layer soil with drinking water followed by precipitating for 10 h. The turbidity of raw water ranged from 15 NTU to 110 NTU(NTU: Normal turbidity unit).

### 2.2 Full-scale test

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We selected Erlong Water Treatment Plant in Bin County of Heilongjiang province in northeast China as the field sample. In consideration of its use of PACl coagulant, its typically regular technological process of coagulation/flocculation, and its steady treating quality, the results will be good references for many other similar water treatment plants in China[10].

Table 1 lists some factors of Erlong Water Treatment Plant. Raw water quality fluctuates within a relatively narrow range (turbidity: 20−100 NTU; aluminum concentration: 0.1 − 0.2 mg/L). Even though temperature is much lower in November than in June, aluminum concentration in raw water is 0.12 mg/L in June and increases to 0.2 mg/L in November, while turbidity is 20 NTU in June and 80 NTU in November.

The plant adopted the conventional drinking water treatment process. Sedimentation tank included a slope-tube group and a little-distance-plate group, and remained operating well with a regular residual turbidity of post-precipitation water was lower than 5.0 NTU.

Coagulant dosage was automatically controlled by a set of automatic measuring-controlling system (type: SG-3000A).

### 2.3 Analytical methods

Aluminum concentration was measured by using the colorimetric method. Aurincarboxylic acid is the coloring agent. Aluminum was complexed by aurincarboxylic acid at pH 4.0−4.2. The absorbance was read at 520 nm. The minimum detection limit for this method ranged from 0.01 to 0.40 mg/L, accuracy was 92.3%−102.1%, and the precision (relative standard deviation) was 3.2%−8.6%. Turbidity was measured by using a ratio turbidimeter (Hach Company) in the laboratory.

## 3 DISCUSSION AND ANALYSIS

### 3.1 Influence of PACl dosage on residual aluminum level

The influence of aluminum-based coagulant dosage plays an important role in residual aluminum concentration[11−15]. It was reported to be 40%−50% of opportunity to increase aluminum concentration in drinking water over the concentrations in the raw water in plants using aluminum-based coagulants. In a U.S. EPA survey of 186 water utilities, Millert et al found that after coagulation with aluminum salts, the aluminum concentration in the treated water varied from 0.01 to 2.37 mg/L[4].

Therefore some tests were designed to study the relationship of PACl and treated water quality (residual aluminum concentration and residual turbidity etc). The results are presented in Fig. 1.

Although the data are not enough to achieve a solid regulation, the trend is clear. Both residual aluminum concentration and residual turbidity indicate the same tendency. Firstly, Both values of residual aluminum concentration and residual turbidity decrease with the increase of dosage of PACl. Secondly, the values begin going up when the dosage excesses some limit. Table 2 shows the results analysis. For example, in Fig. 1(a), while commercial dosage of PACl rises from 5 mg/L to 20 mg/L, the value of residual turbidity goes down from 9.4 NTU to 4.2 NTU correspondingly. When commercial dosage of PACl exceeds 20 mg/L, residual turbidity rises from 4.2 NTU to 8.1 NTU (correspondingly dosage from 20 mg/L up to 35 mg/L). The latter average rate (0.26 NTU·L/mg) is a little less than the former (absolute value 0.35 NTU·L/mg). For residual aluminum concentration the value changes from 0.13 mg/L to 0.11 mg/L with PACl dosage from 5 mg/L to 10 mg/L. When commercial dosage of PACl goes up from 10 mg/L to 35 mg/L, residual concentration aluminum concentration rises from 0.11 mg/L to 0.19 mg/L accordingly. But the latter average rate (0.032) is larger than the former (absolute value 0.004).

In Fig. 1(b) the data show the similar trend as that in Fig. 1(a). Considering that turbidity of raw water (105 NTU) was higher than that in Fig. 1(a), range of commercial dosage of PACl was adjusted from 15 mg/L to 45 mg/L. While commercial dosage of PACl rose from 15 mg/L to 30 mg/L, the value of residual turbidity went down from 8 NTU to 4.6 NTU correspondingly. But after commercial dosage of PACl exceeded 30 mg/L, re-

**Table 1** Factors of Erlong water treatment plant

| Production/ $(m^3 \cdot d^{-1})$ | Water resource | Raw water quality | | | |
|---|---|---|---|---|---|
| | | Time | Raw water turbidity/NTU | Raw water aluminum concentration/ $(mg \cdot L^{-1})$ | Raw water temperature/℃ |
| 4 000 | Erlonghu reservoir | Total year | 20−100 | 0.1−0.2 | − |
| | | November (average) | 80 | 0.20 | 0.5 |
| | | June (average) | 20 | 0.12 | 15 |

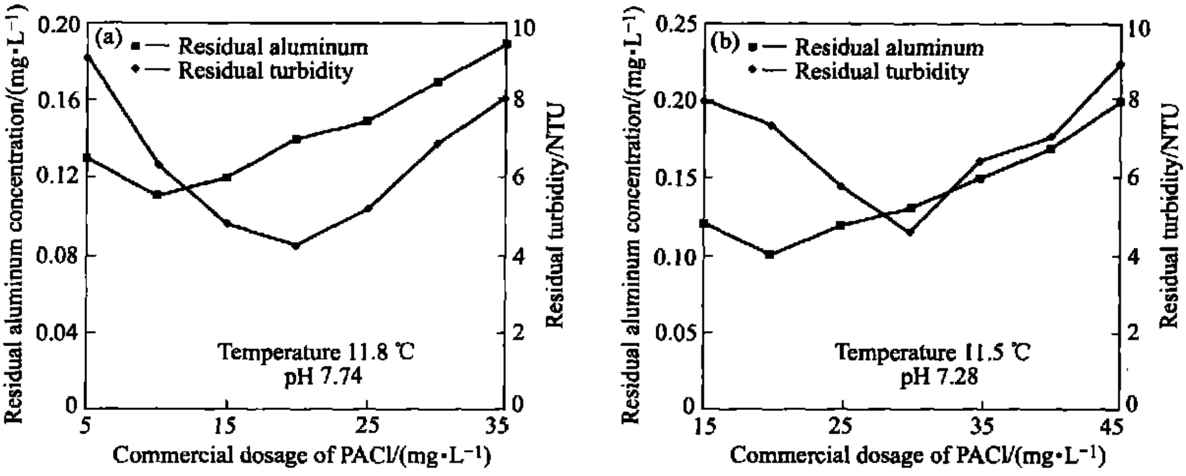


**Fig. 1** Influence of coalgulant dosage on residual turbidity and residual aluminum concentration
(a) —Raw water turbidity 35 NTU; (b) —Raw water turbidity 105 NTU

**Table 2** Results analysis of Fig. 1

| Item | Fig. 1(a) | | Fig. 1(b) | |
|---|---|---|---|---|
| | Residual turbidity | Residual aluminum | Residual turbidity | Residual aluminum |
| Optimal-dosage (PACl) / ($mg \cdot L^{-1}$) | 20 | 10 | 30 | 20 |
| Former average rate① | − 0.35 NTU•L/mg | − 0.004 | − 0.23 NTU•L/mg | − 0.004 |
| Latter average rate① | 0.26 NTU•L/mg | 0.032 | 0.29 NTU•L/mg | 0.004 |
| Total average rate① | − 0.043 NTU•L/mg | 0.002 | 0.033 NTU•L/mg | 0.003 |
| Relatively total average rate②/ ($\% \cdot L \cdot mg^{-1}$) | 0.5 − 1.0 | 1.1 − 1.8 | 0.4 − 0.7 | 1.5 − 2.5 |

① Calculating equation: $\frac{\text{turbidity range}}{\text{dosage range}}$ and $\frac{\text{aluminum range}}{\text{dosage range}}$

② Calculating equation: $\frac{\text{total average rate/maximum}}{\text{total dosage range}}$ and $\frac{\text{total average rate/minimum}}{\text{total dosage range}}$

sidual turbidity rose from 4.6 NTU to 9 NTU (correspondingly dosage from 30 mg/L up to 45 mg/L). The latter average rate (0.29 NTU•L/mg) is a little more than that of the former (absolute value 0.23 NTU•L/mg). For residual aluminum concentration the value changed from 0.12 mg/L to 0.10 mg/L with PACl dosage from 15 mg/L to 20 mg/L. After commercial dosage of PACl went up from 20 mg/L to 45 mg/L, residual aluminum concentration rose from 0.10 mg/L to 0.2 mg/L accordingly. But here the latter average rate (absolute value) is equal to that of the former at a value of 0.004.

The trend suggests that PACl dosage is an important factor. Its importance can be described as follows. First of all, the dosage of PACl influences the quality of treated water significantly. There is an optimal dosage value to control treatment effects. Secondly, PACl dosage has an optimal value, at which residual turbidity reaches the minimum. This optimal value can be called optimal-dosage-to-turbidity. PACl dosage also has another optimal value, at which residual aluminum reaches the minimum. This optimal value is called optimal-dosage-to-aluminum. Test results indicate that the optimal-dosage-aluminum is lower than the optimal-dosage-turbidity. The authors believe that during coagulation, a tendency occurs as follows. On one hand, with the increase of dosage, the efficient availability of coagulant is lowered; "leakage" increases, so that residual aluminum concentration will go up. On the other hand, with the removal of turbidity, aluminum can be removed to some extent. At a low dosage, coagulant works well, and residual turbidity goes down with the increase of coagulant dosage (residual aluminum also goes down correspondingly). When dosage exceeds the optimal-dosage-to-aluminum, the influence of "alum-leakage" takes the superiority, so residual aluminum concentration starts to increase. By the time dosage exceeds the optimal-dosage-to-turbidity, both the "alum-leakage" and the increase of residual turbidity contribute to the increase of residual aluminum concentration.

Since the relatively total average rate of residual aluminum concentration is more than that of residual turbidity (Table 2), it may be suggested that aluminum concentration is more easily subject to the influence of alum-coagulants than turbidity is. The authors are sure that it is better for water treatment plants to adopt optimal-dosage-to-aluminum instead of optimal-dosage-to-turbidity, which can decrease residual aluminum concentration and residual turbidity of treated water simultaneously.

### 3.2 Relativity of residual turbidity and residual aluminum concentration of post-precipitation

Residual aluminum consists of dissolved and particulate components. Because of the low solubility, dissolved aluminum component has much lower concentration than particulate component. Particulate aluminum component can be removed easily with the removal of turbidity colloid. Certain relativity can be assumed between residual turbidity and residual aluminum concentration. In Bin County Water Plant some tests were designed to find out the relativity.

The high-temperature varies from 8 to18 ℃ in June and July while the relatively low-temperature ranges from 0 to 2 ℃ in October and November. The coagulant dosages were adjusted according to raw water turbidity by the automatic controlling system in water plant, or by manual adjustment in laboratory.

In consideration of the relatively small quantity of production and the enough spare volume of clear water reservoir, Bin County Water Plant usually runs only in the daytime. Accordingly water samples of post-precipitation and post-filtration were selected and measured every 1.5 − 2 h in the daytime.

Turbidity, aluminum concentration and pH of raw water and selected water samples were measured accordingly. The results were presented in Fig. 2. Considering the safety of production data above 10 NTU was only four dots. But these four dots are important to help draw the line of the relativity out. Residual aluminum concentration of post-precipitation water roughly appears increasing and decreasing with the increase and decrease of residual turbidity correspondingly. Turbidity went up from 3 NTU to 18 NTU; aluminum changed from 0.14 mg/L to 0.23 mg/L with a total average velocity of 0.006 mg/(L•NTU). Because residual aluminum concentration of treated water is believed to easily drop down to 0.05 mg/L, if residual aluminum concentration of post-precipitation is beneath 0.15 mg/L, a dashed line at 0.15 mg/L of residual aluminum is also presented. From the chart 7 NTU has been observed as a critical point. When turbidity is lower than 7 NTU (dots: 3 − 7.2 NTU), almost all the dots are below the dashed line (except the dot: 6 NTU, 0.16 mg/L), and the average velocity is 0.002 4 mg/(L•NTU), much less than the average velocity of turbidity over 7 NTU (dots: 8 − 18 NTU), which is 0.007 3 mg/(L•NTU). All the dots over 7 NTU mean a residual aluminum higher than 0.15 mg/L.

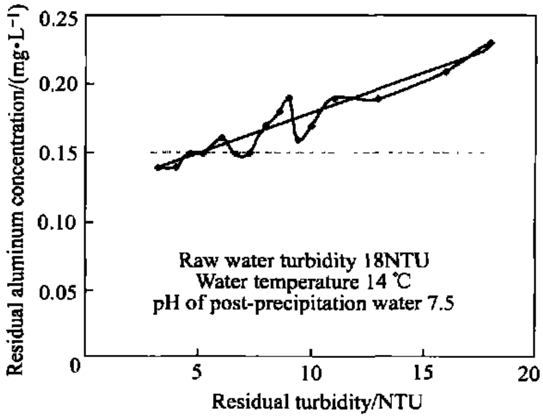


**Fig. 2** Relativity between residual turbidity and residual aluminum concentration of post-precipitation

The trend line (shown in Fig. 2) also indicates this. Using calculus parlance, the regression line's formula ($y$: residual aluminum concentration; $x$: residual turbidity) is $y = 0.000\,037x^2 + 0.005\,104x + 0.122\,588$ ($r = 0.946$).

So the first derivative $\frac{dy}{dx} > 0$, the second derivative $\frac{d^2y}{dx^2} > 0$. The results show a rough estimation that even though $y$ (residual aluminum concentration) is progressively increasing with $x$ (residual turbidity), increasing velocity ($\frac{dy}{dx}$) is different, and also is progressively increased with $x$. Additionally the formula implies that in post-precipitation water residual aluminum won't be removed completely. That is to say residual aluminum concentration has the extremum.

In one way, dissolved aluminum exists in a majority of ion-aquatic state, which is difficult to be removed directly because of its tiny diameter. Dissolved aluminum components can include complexes with natural organic matter, fluoride, phosphate, sulfate, and hydroxyl ions. Coagulation-precipitation results in the removal of these complexes; so dissolved aluminum is removed indirectly. Normally the concentration of these complexes is only a little and the removal effect is little. In another way, particulate aluminum components can be removed with turbidity colloids easily. The removal of particulate aluminum is accompanied by the removal of turbidity and this removal effect is much more significant than the effect from the complexes. The tendency is that residual aluminum concentration can decrease as residual turbidity decreases. While residual aluminum concentration is decreased when residual turbidity is lowered, the portion of dissolved aluminum component in residual aluminum goes up, and the decreasing velocity will slow down. With regard to the extremum, which means at that time the effect of decreasing residual turbidity is also very little, it can be assumed to be consisted of mostly dissolved aluminum component and a few tiny particulate aluminum. Obviously the extremum is variable because of the different water temperature and pH.

In conclusion, the method of decreasing the components of residual aluminum concentration can be divided into the removal of particulate aluminum and the decrease of dissolved aluminum. The removal of particulate aluminum can result from the decreasing of residual turbidity. The decrease of dissolved aluminum species mainly relies on the adjustment of pH under different water temperatures.

### 3.3 Influence of water temperature on residual aluminum concentration

The following tests provide a way to study the influence of water temperature on dissolved aluminum, and search for some appropriate methods to decrease dissolved aluminum concentration. In order to keep the comparability, residual turbidity of post-precipitation remains 7 NTU through the coagulant-dosage-controlling system. And this is the most important premise. It is assumed that particulate aluminum concentration will be little and keeps the same if the residual turbidity remains (7.0 ± 0.1) NTU. This assumption comes from the analysis and discussion presented above. Furthermore, the change of residual aluminum concentration reflects the change of dissolved aluminum concentration well.

Data is presented in Fig. 3. Because this test had some intervals, the continuous data of water temperature was not achieved. Water temperature was divided into three phases as 0 – 2 ℃, 8.5 – 10.5 ℃ and 14 – 16 ℃. Even though the dots seem too random to give a good support of a certain regulation, with the increasing of water temperature, residual aluminum concentration shows an increasing trend as the trend line shows. At water temperature 16 ℃ the residual aluminum concentration reaches 0.18 mg/L, which is nearly twice as much as that when water temperature is 0.5 ℃. This is because the solubility of particulate aluminum species increases greatly with water temperature[16-18], dissolved aluminum increases, and total residual aluminum increases as well. When water temperature is higher than 15 ℃, the concentration of residual aluminum is over the dashed line of 0.15 mg/L. It means a more serious task to control residual aluminum of treated water in higher temperature, especially in summer's continuous higher temperature. When searching for a quantitative description of the correlation of temperature and aluminum, we only find that the solubility constant ($Al(OH)_3(s) \rightleftharpoons Al^{3+} + 3OH^-$) has been given as $10^{-32}$ (chemical handbook 1997), $1.3 \times 10^{-32}$, $2 \times 10^{-33}$ etc. Even there is no accurate model of the occurrence of aluminum in water. More tests are needed to substantiate any conclusion.

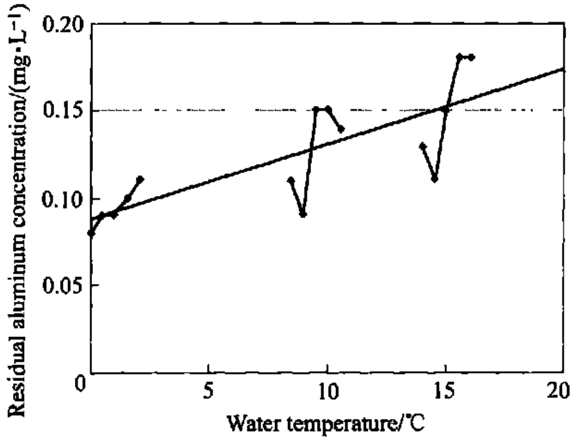


**Fig. 3** Influence of water temperature on residual aluminum concentration
(pH value of post-precipitation: 7.5)

Authors also observed another paradoxical phenomenon if residual turbidity was not kept at 7 NTU in the process. When water temperature is relatively low (below 2 ℃), residual aluminum concentration is also likely to go up. Fig. 4 shows the results. Nearly all the data is above 0.15 mg/L. In the first phase residual aluminum concentration changes from 0.23 mg/L to 0.19 mg/L, correspondingly in the second phase 0.18 mg/L to 0.17 mg/L and in the last phase 0.17 mg/L to 0.18 mg/L. The dots at which water temperature are above 10 ℃ illustrate that residual aluminum concentration fluctuates at an average of 0.174 mg/L. While residual aluminum concentration apparently increases when temperature is below 2 ℃. The average of residual aluminium concentration of 0 – 2 ℃ reaches 0.214 mg/L. The reason is that the treatment efficiency of PACl coagulant decreases significantly. Both residual turbidity and residual aluminium concentration increase at the first phase. Residual turbidity holds an average of 9.44 NTU, much higher than the controlled value of 7 NTU. Though the concentration of dissolved aluminium species drops because of the lower solubility at low temperature, higher residual turbidity brings about more particulate aluminium concentration. And the latter is superior in numbers, which results in the increase of total residual aluminum.

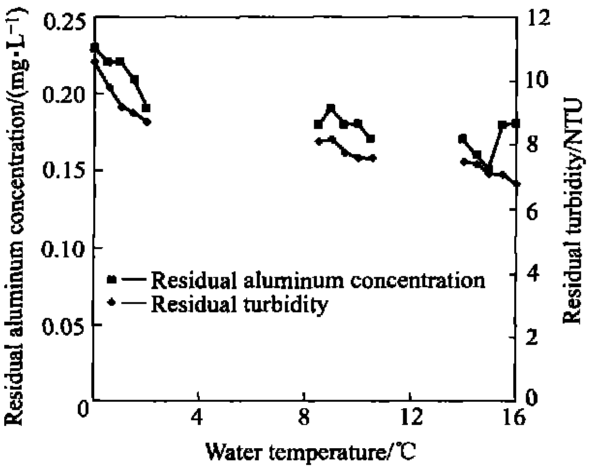


**Fig. 4** Average values of residual aluminum and residual turbidity of post-precipitation water

### 3.4 Influence of pH on residual aluminium during coagulation

In a weak-alkali circumstance particulate aluminum species in water mainly consists of Al-$(OH)_3$(s) or gibbsite, which is an amphoteric oxyhydrate. Unquestionably pH is a key factor of $Al(OH)_3$ solubility. Furthermore the removal of particulate aluminum species is technically feasible by decreasing residual turbidity. So the influence of pH on residual aluminum lies in three aspects: firstly, influencing the efficiency of alum-coagulant or PACl; secondly, influencing the concentration of dissolved aluminum, and at the last, influencing the feasibility of removal or decrease of residual aluminum. Benschoten ever proposed that pH should be more suitable for describing the situation of decreasing residual aluminum concentration[17].

This part of test was carried out with some difficulties because Bin-xian Water Treatment Plant didn't adjust pH during the whole process. Some jar-tests were designed according to the quality of raw water. By fitting certain parameters such as turbidity of raw water, water temperature, dosage of PACl, the pH was adjusted in accordance with the pH range (7 − 8.5) of Bin-xian Water Treatment Plant. The adjustment was achieved by adding either 0.1 mol/L NaOH or 0.1 mol/L HCl. The pH meter was recalibrated for different temperature using the correspondent pH standards. Requested data was residual turbidity, residual aluminum concentration and pH of post-precipitation water. The data with residual turbidity of (7.0±0.1) NTU is available for analyzing the correlation of pH and residual aluminum concentration. By fitting other parameters, the change of residual aluminum concentration can be assumed to result from the different pH values. The plot is shown in Fig. 5. Clearly the concentration of residual aluminum here is dependent on pH value. Moreover the tendency is not simple. Dots are a bit scattering. So the tendency line is given. The dashed line indicates the limit of residual aluminum is 0.15 mg/L. In the range of pH 7.05 − 7.84 all dots show concentration of residual aluminum is below 0.15 mg/L, and outside the range, residual aluminum shows an increasing trend in both directions. On purpose to control the residual aluminum, the discussion put emphasis upon how the change of pH influences the change of residual aluminum.

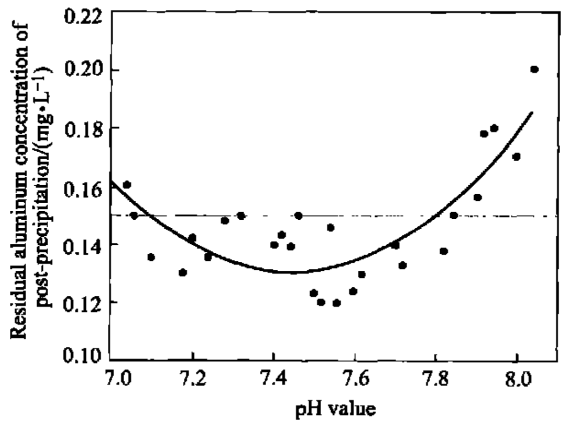


**Fig. 5** Correlation of pH value and residual aluminum
(Turbidity of raw water 80 NTU; temperature 14 ℃)

The tendency line has one valley. The valley shows such a trend: there is one down branch, which means residual aluminum concentration going down with pH value increasing, and the other is an up branch, which means residual aluminum concentration increasing as well as pH value increasing. So the valley means there is an optimal pH value, which can help to minimize residual aluminum.

Furthermore, Fig. 5 shows the optimal pH value is around a pH value of 7.44, and the correspondent minimum residual aluminum concentration is as low as 0.13 mg/L, which is 35% lower than the concentration of residual aluminum of pH value 8.04. The tendency line also shows that residual aluminum concentration of post-precipitation is likely to exceed 0.15 mg/L within certain range of pH value (e.g. over 7.80, or below 7.10), and such ranges frequently occur in water treatment plants. The suggestion is that adjusting pH value to the range of 7.10 − 7.80 which would be a feasible and efficient way to control residual aluminum concentration of treated water.

Searching for a rational explanation, in an environment of pH value 7.0 − 8.0, aluminum species in water mainly consists of $Al(OH)_3(s)$, $Al_{13}(OH)_{34}^{5+}$, $Al(OH)_4^-$, $Al^{3+}$. Interacting reactions are shown as[19, 20]:

$$Al(OH)_3(s) \leftrightarrow Al^{3+} + 3OH^-$$

(solubility constant $K_{sp}$)

$Al^{3+} + 4H_2O \leftrightarrow Al(OH)_4^- + 4H^+$

(equilibrium constant $K_1$)

$13Al^{3+} + 34H_2O \leftrightarrow Al_{13}(OH)_{34}^{5+} + 34H^+$

(equilibrium constant $K_2$)

So

$$[Al^{3+}] = K_{sp}/[OH^-]^3 = K_{sp}K_w^{-3}[H^+]^3 \quad (1)$$

$$[Al(OH)_4^-] = K_1[Al^{3+}]/[H^+]^4 = K_1K_{sp}K_w^{-3}/[H^+] \quad (2)$$

$$[Al_{13}(OH)_{34}^{5+}] = K_2[Al^{3+}]^{13}/[H^+]^{34} = K_2K_{sp}^{13}K_w^{-39}[H^+]^5 \quad (3)$$

In that the concentration of $Al^{3+}$ is scarce when pH value is around the neutral point 7.0, $[Al^{3+}]$ has not been taken account of. So the change of concentration of dissolved aluminum in residual aluminum mostly comes from the changes of $[Al(OH)_4^-]$ and $[Al_{13}(OH)_{34}^{5+}]$. For want of accurate $K_{sp}$, $K_1$ and $K_2$, concrete quantitative calculation cannot be conducted. Qualitative analysis is the appropriate method. Eqn.(2) tells that $[Al(OH)_4^-]$ has an inverse relation to $[H^+]$, which means, if pH increases, $[Al(OH)_4^-]$ will also increase. However Eqn.(3) shows that $[Al_{13}(OH)_{34}^{5+}]$ is linear to $[H^+]^5$, that is to say, $[Al_{13}(OH)_{34}^{5+}]$ will decrease together with pH value's increasing. Considering that when pH value is bigger than 7.0, the change of concentration of dissolved aluminum mostly comes from the changes of $[Al(OH)_4^-]$ and $[Al_{13}(OH)_{34}^{5+}]$, the sum of $[Al(OH)_4^-]$ and $[Al_{13}(OH)_{34}^{5+}]$ turns out an extremum, which is the reason why the valley is there. The following equations show the deduction process:

$$S = [\text{sum}] = [Al(OH)_4^-] + [Al_{13}(OH)_{34}^{5+}] = K_1K_{sp}K_w^{-3}/[H^+] + K_2K_{sp}^{13}K_w^{-39}[H^+]^5 = A/[H^+] + B[H^+]^5$$

$(A = K_1K_{sp}K_w^{-3},\ B = K_2K_{sp}^{13}K_w^{-39})$

$(C = [H^+])$

$$\frac{dS}{dC} = -\frac{A}{C^2} + 5BC^4 = 0$$

Solution of the equation is

$$C = \sqrt[6]{\frac{A}{5B}}$$

And that

$$\frac{d^2S}{dC^2} = 2\frac{A}{C^3} + 20BC^3 > 0$$

Then the extremum is a minimum.

Another point of view is about the correlation of temperature and the optimal pH. Because water temperature greatly influences the values of $K_1$, $K_2$, $K_{sp}$, $K_w$, the optimal pH may have correlation with water temperature[18]. Fig. 6 provides some information for the discussion.

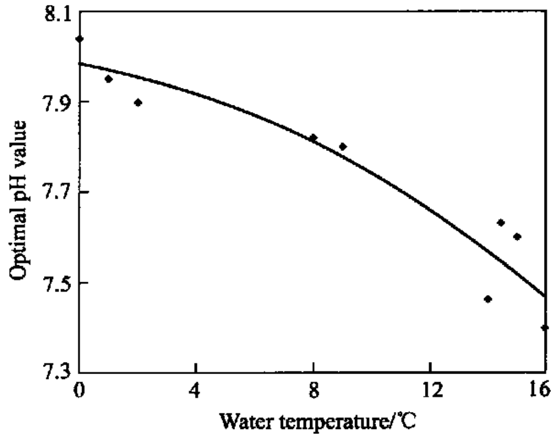


**Fig. 6** Correlation of water temperature and optimal pH value

The curve shows the optimal pH value goes down quite rapidly following temperature's increasing. For example, the optimal pH versus water temperature 1 ℃ is 7.95, when water temperature rises to 16 ℃, the corresponding optimal pH is only 7.40. The former analysis has given such reactions as

$Al(OH)_3(s) \leftrightarrow Al^{3+} + 3OH^- \quad K_{sp}$

$Al^{3+} + 4H_2O \leftrightarrow Al(OH)_4^- + 4H^+ \quad K_1$

$13Al^{3+} + 34H_2O \leftrightarrow Al^{13}(OH)_{34}^{5+} + 34H^+ \quad K_2$

If water temperature increases, all the values of $K_{sp}$, $K_1$, and $K_2$ will increase. That is to say, the reactions balance will process in the right direction, and concentration of dissolved aluminum species will increase significantly as well. By the time, in order to achieve an environment of appropriate pH for decreasing residual aluminum, the optimal pH value will decrease, so that the balances will likely be kept.

## 4 CONCLUSIONS

Dosage of alum-coagulant or PACl influences the residual aluminum greatly. There is an optimal-dosage-to-aluminum, which is a bit less than the optimal-dosage-to-turbidity. It is suggested that in water treatment plants the dosage of alum-coagulant or PACl should benchmark on the optimal-dosage-to-aluminum in order to achieve effects in decreasing aluminum and turbidity synchronously.

It is also proposed that in water treatment process decreasing residual aluminum can be divided into two independent methods. One is to decrease, even remove, the particulate aluminum component, the other is to decrease dissolved aluminum concentration. Decreasing turbidity can bring about an ideal effect in decreasing particulate aluminum concentration, and this way has been proved to be technically feasible. There is a given value of residual turbidity of post-precipitation. Test results show that the given value is 7 NTU. If residual turbidity of post-precipitation is lower than the given value, the particulate aluminum species can be removed on the whole. The given value can be made a guide to definite dosage of coagulant.

If water temperature goes higher, the solubility of particulate aluminum will increase, that is, residual aluminum concentration will increase even though the residual turbidity remains the same. Then adjusting residual turbidity or coagulant dosage can do some help in water treatment plants.

With residual turbidity staying the same, optimal pH value at different temperature corresponds a different minimum dissolved aluminum concentration. The aluminum removal can be improved. The optimal pH value changes with water temperature. Data shows if water temperature increases the optimum will decrease.

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