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Process design of water treatment plant on groundwater with high hardness in Yucheng

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ABSTRACT

Groundwater quality in Yucheng city shows that total hardness was 494–612 mg/L, total iron was 0.35–3.43 mg/L, total dissolved solids were 1,083–1,390 mg/L, and turbidity was 7.6–21.7 NTU. According to groundwater quality, aeration-lime softening-conventional water treatment process was selected by bench-scale experiment and the treated water quality reached the limiting value of "Standards for drinking water quality" (GB5749-2006). The new water plant was designed with water supply of $3.0 \times 104\,m^3/d$, the occupied area of 2.14 ha and population designed of 23.0 million. This study may provide references for identical and similar water treatment plant design.

Keywords: Lime; Total hardness; Groundwater; Process parameters

1. Introduction

The city of Yucheng is located in the northwest of Shandong Province and the middle reach of the Tuhai River. In recent years, with the development of Yucheng High-Tech Industrial Development Zone and the expansion of urban area, the construction of urban water supply facilities were far behind the objective water demand.

At present, the water consumption of Yucheng city is about $5 \times 10^4\,m^3/d$. Urban water supply was included in centralized water supply and produced by a water supply company and self-drilled well. The supply range of the water supply company was only part of the residential area in the city, because the number of self-drilled wells had reached 70. Now, because the limited daily supply capacity of the water supply plant, it is necessary to project a new water plant.

The new water plant was designed with water supply of $3.0 \times 10^4\,m^3/d$, the area of 2.14 ha, and population designed of 23.0 million. Water source wells included shallow and deep wells, of which well spacing was 100 m. The output of a single deep well was $65.0\,m^3/h$, of which the depth was 400–450 m. The output of a single shallow well was $80.0\,m^3/h$, of which the depth was 120–150 m. Twelve shallow wells and 8 deep wells were drilled, in which 2 wells were prepared for backup use. Pumping stations of wells were built on the ground in the pattern of one pump for one well and connected to the waterworks by water pipelines.

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The construction period of this project was 18 months, including two phases. The first phase of the project was completed before the end of October 2011, the second phase and other auxiliary plant works would be finished by the end of December 2012. The construction of the project plays an important role in solving the problem of the urban water supply and improving the quality of water supply, as well as meeting the needs of the urban area life and part of industrial consumption.

2. Water quality analysis

With the continuous development of the upper reaches of the Yellow River, the water supply quantity of the Yellow River was decreasing year by year, as a result the utilization of the Yellow River has been restricted. The urban rivers were seasonal rivers except the Tuhai river which was ranked tail water of the Yellow River, so the groundwater was chosen as the water source of the water treatment plant, which was abundant from the southeast of Sun Village to the northeast of the Shinv river. Quality conditions of groundwater in Yucheng city were shown in Table 1.

The groundwater in Yucheng city contains high salinity, the most ions such as total hardness (high temporary hardness), total iron, turbidity, and total dissolved solids exceeded the limiting value of "Standards for drinking water quality" (GB5749-2006). Water softening mainly included pharmacy softening method that was based on the principle of solubility product and ion-exchange softening method which was based on the ion-exchange principle [1]. With advancements in membrane technology, reverse osmosis has become a major technology for softening and desalination [2]. In water treatment, commonly used softening processes are chemical precipitation and ion-exchange [3]. High project costs, high operating costs and complicated operation existed in the ion-exchange softening method [4], but lime pharmacy softening method had the advantage of low price, extensive source, and low operating costs, processing with flocculation at the same time, which could not only remove heavy metal cations, but also reduce the turbidity of water [5]. Usually, lime pharmacy softening method was used to deal with the high temporary hardness and alkalinity water [6]. Turbidity, total hardness, total iron, and total dissolved solids could be reduced by aeration-lime softening-conventional water treatment process, the indexes of treated water quality can reach the limiting value of "Standards for drinking water quality" (GB5749-2006).

Table 1
Analysis of the raw groundwater quality

Item	Value
pH	7.27–7.81
Turbidity/NTU	7.6–21.7
Total hardness/(mg/L)	494–612
Total iron/(mg/L)	0.35–3.43
TDS	1,083–1,390
Cl^-/(mg/L)	168–175
SO_4^{2-}/(mg/L)	217–234
Total alkalinity/(mg/L)	477–508

3. Experimental

3.1. Procedures

A certain amount of $Ca(OH)_2$ (AR, Solidstate) were added into groundwater sample (1,000 mL). Mixing speed was 300 r/min and mixing time was 2 min. Flocculation speed was 50 r/min and flocculation time was 10 min followed by 10 min sediment. Then, 150 ml water samples were taken to measure.

3.2. Analytical methods

Total hardness, total iron, and total dissolved solids indexes were measured according to the national standard analytical methods. Turbidity was measured with turbidimeter, and pH was determined with pH analyzer.

4. Results and discussion

4.1. Milk of lime softening experiment

A certain amount of $Ca(OH)_2$ were added into groundwater sample, neutralization reaction occurred OH^- in $Ca(OH)_2$ and H^+ in groundwater, which made the carbonate equilibrium shifted to the direction of generating CO_3^{2-}. Because of dissociated HCO_3^-, not only total alkalinity, dissolved solids and hardness were reduced, but also Ca^{2+}, Mg^{2+} and free dissolved carbon dioxide were removed.

Fig. 1 shows that total hardness decreased significantly with the increase in lime dose. With lime dosage of 840 mg/L, the minimum total hardness was reduced to 92.19% of the initial value. The total hardness and the turbidity were found to be more efficiently removed with a lime dosage of 140 mg/L, under the condition of which the total hardness reached a concentration of 402 mg/L and the turbidity was 2.35NTU, which reached the requirements of the

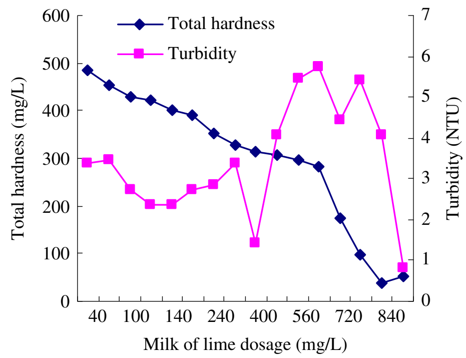

Fig. 1. Effect of milk of lime dosage on total hardness and turbidity.

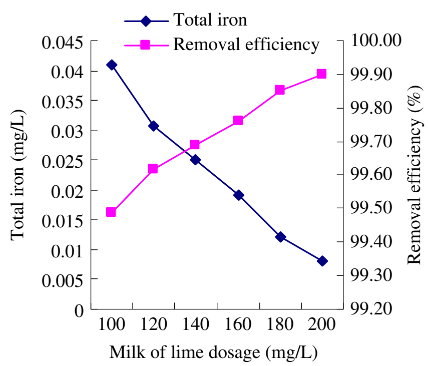

Fig. 2. Effect of milk of lime dosage on total iron.

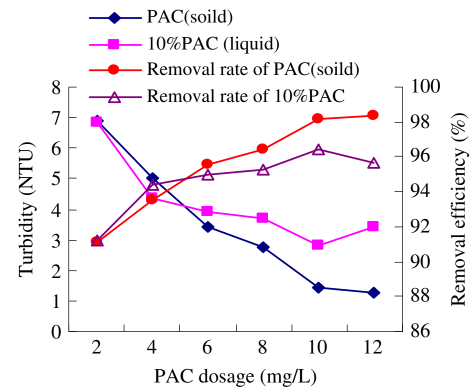

Fig. 3. Effect of PAC dosage on turbidity.

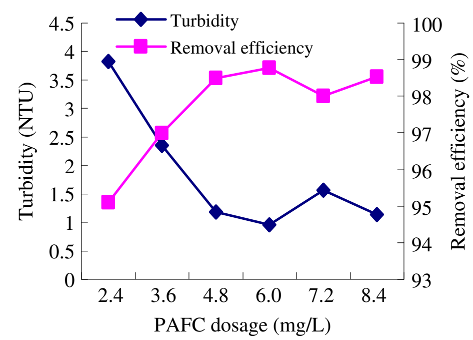

Fig. 4. Effect of PAFC dosage on turbidity.

filter influent water turbidity. Fig. 2 illustrated the total iron concentration changed with the increase in lime dose. It showed that the removal efficiency of total iron was more than 99%. When the dosage exceeded 200 mg/L, total iron concentration was almost 0 mg/L. It seemed that the 140 mg/L dosage of lime be the most efficient dosage to remove total hardness and total iron.

4.2. Coagulation-sedimentation experiment

Several coagulants were tested in this experiment. PAC (solid), 10%PAC (liquid), and PAFC were determined with better removal efficiency. The contrast experiment research results on groundwater with them were shown in Figs. 3 and 4.

Fig. 3 shows that the removal efficiency of PAC (solid) was better than that of the 10%PAC (liquid). With PAC (solid) dosage of 8 mg/L, the turbidity was reduced to 2.78NTU, which reached the requirements of the filter influent water turbidity. Fig. 4 showed that the turbidity was reduced to 2.35NTU when PAFC dosage was 3.6 mg/L, and the turbidity was 96.99% of the initial value, which was better than PAC. However, PAFC had a certain degree of corrosion resistance. PAC (solid) was selected to be coagulant in this experiment and the optimum dosage was 8 mg/L.

4.3. Milk of lime dosage on pH of treated water

Fig. 5 shows that, as expected, the pH was increasing with the increase in lime dose. This corroborates with the fact that lime is a basic component whose dose increases the solution pH. When milk of lime dosage was less than 240 mg/L, the pH value of treated water was lower than the pH after adding milk of lime. It was explained that the OH^- of milk of lime reacted with alkalinity in water. As milk of lime dosage exceeded 240 mg/L, the pH value of treated water was higher than the pH after adding milk of lime. It was because that the OH^- of milk of lime was excessive and only part of OH^- reacted with alkalinity of low concentration in water. When milk of lime dosage was 140 mg/L, the pH value of treated water was 8.76, which should be adjusted by acid to reach the limiting value of "Standards for drinking water quality" (GB5749-2006).

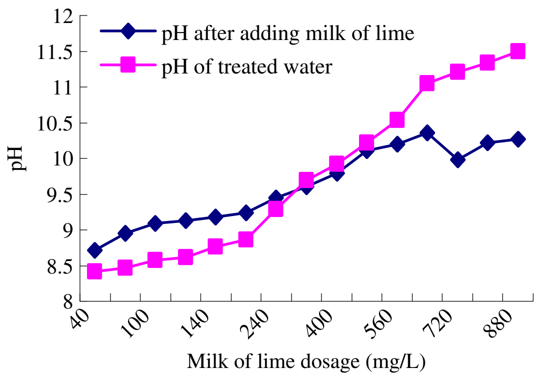

Fig. 5. Effect of Milk of lime dosage on pH.

4.4. pH adjustment experiment

For studying on the adjustment of the pH value of treated water, different volumes of concentrated sulfuric acid (0.18 mol/L) and hydrochloric acid (0.12 mol/L) were added into treated water (1,000 mL). The experimental results were shown in Figs. 7 and 8.

Figs. 6 and 7 shows that concentrated sulfuric acid of 0.18 mol/L had a better performance than hydrochloric acid of 0.12 mol/L. As the value of pH reached about 8.5, dosage of concentrated sulfuric acid was lower than that of hydrochloric acid. As the value of pH was about 6.5, dosage of concentrated sulfuric acid was 18.6 ml, and dosage of hydrochloric acid was 80 ml. However, it is suggested that hydrochloric acid should be used to adjust the pH value, considering the high content of sulfate in the raw water.

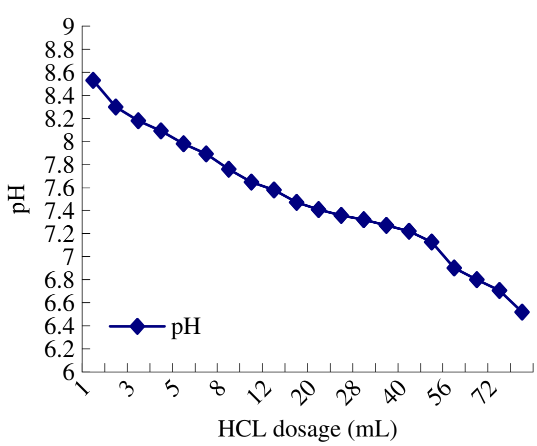

Fig. 6. Effect of HCl dosage on pH.

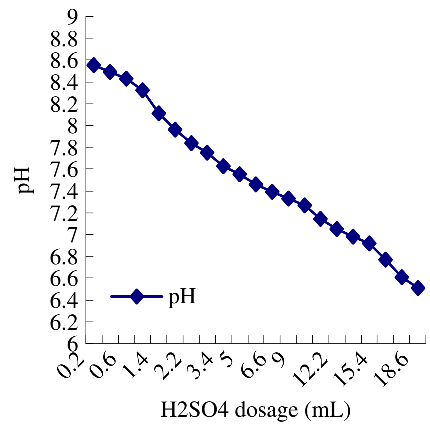

Fig. 7. Effect of H_2SO_4 dosage on pH.

According to groundwater quality of Yucheng city, aeration-lime softening-conventional water treatment process was selected. The process conditions were identified by study of experiment, including milk of lime dosage was 140 mg/L, dosage of PAC was 8 mg/L, mixing speed was 300r/min and mixing time was 2 min, flocculation speed was 50r/min and flocculation time was 10 min followed by 10 min sediment. Treated water was filtered through 0.45-µm membrane, all water quality indexes reached the limiting value of "Standards for drinking water quality" (GB5749-2006). The quality of raw and treated water were shown in Table 2.

Table 2
Analysis of the raw and treated water quality

	Raw water	Treated water
pH	7.7	7.5
Turbidity (NTU)	78	0.5
Total hardness (mg/L)	512	402
Total iron (mg/L)	8	0.008
TDS (mg/L)	1,390	963

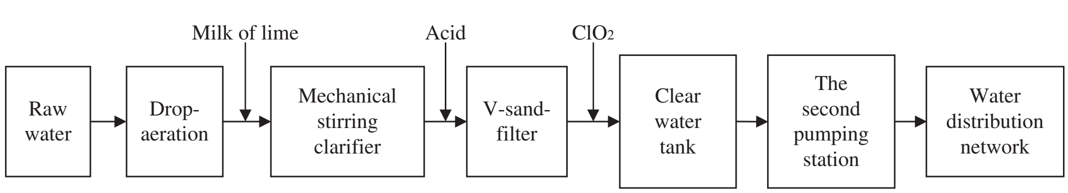

Fig. 8. Process flow of the new plant.

5. Process design

5.1. Process flow

The iron in raw water was oxidized by drop-aeration process. Total hardness was removed by adding milk of lime. Hydrochloric acid was used to adjust the pH value. The water was transported into clear water pond after filtered with V-sand-filter. The treated water, after disinfected with chlorine dioxide, was pressurized by the water supply pumping station, then transported into the water supply network. Process flow was shown in Fig. 8.

5.2. The water plant plane layout

Water wells were located in the south of the reception office, the main structures were built in the northwest of the reception office, which were shown in Fig. 9.

5.3. The main structures

5.3.1. The structure of water-dropping aeration

The structure of water-dropping aeration removed iron by the gravity from groundwater under continuous aeration, which was combined with the landscape water. Three-stage water-dropping aeration was designed in this project, which covered an diameter area of about 20 m. Outer diameter of three-stage water-dropping aeration increased from the first to the third water-dropping aeration, which was 10–12 m in turn. Falling water height of the first water-dropping aeration was 1.0 m, and that of the second and third water-dropping aeration were both 0.6 m. Unit discharge was 40 $m^3/(h\,m)$. Water channel was designed at the place of the third water-dropping aeration, conveying water to the next treatment structure with pipelines.

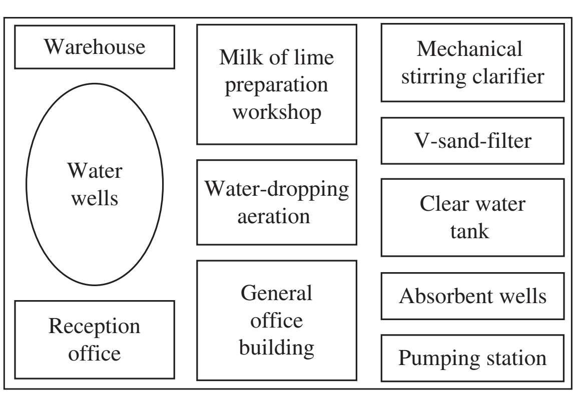

Fig. 9. The plane layout of the new plant.

5.3.2. Mechanical stirring clarifier

Mechanical stirring clarifier was a sludge recycling-based clarifier, which was composed of three parts including the first flocculating chamber, the second flocculating chamber and the third separation chamber. Three mechanical stirring clarifiers were designed, each of processing capacity was 500 m^3/h and its diameter was 17.0 m. The structure of mechanical stirring clarifier was reinforced concrete on the ground. The operation parameters of mechanical stirring clarifier were as follows: Upflow velocity: 0.6–0.77 mm/s, HRT: 1.5 h, velocity of inlet pipe: 0.8–1.6 m/s, flow velocity of triangular groove: 0.5–1.0 m/s, flow velocity of sludge back seam: 150–200 mm/s. The baffle width was 0.1 times larger than the diameter of the second reaction chamber.

5.3.3. Milk of lime adding device

Automatic equipments of milk of lime adding system were selected, the plane size was 42 m × 6.0 m, the size of chemical dosing room was 6.0 m × 9.0 m, the dehydration room size was 6.0 m × 6.0 m, and the underground sludge pool size was 6.5 m × 6.0 m. The storage amount of the lime powder was for its consumption of 10 days. The volume of cylindrical storage house was 85 m^3, and its dimension were as follows: The diameter was 4.5 m, the height was 2.5 m, and the angle of cone bucket was 50°. The capacity of pump for feeding milk of lime was 5 m^3/h. The diameter of lime auxiliary box was 0.8 m, the diameter of the metering box was 1.2 m.

5.3.4. V-sand-filter

V-sand-filter, air supply pumping station and disinfection room were combined together, the plane size of the total construction was 53.05 m × 15.84 m. Four groups of V-sand-filters were designed and arranged in single-line, each of processing capacity was 312.5 m^3/h. The structure of V-sand-filter was frame structure in addition to the reinforced concrete of cell body. Designed filtration rate was 6.03 m/h and the filtration backwash period was 24 h. Air backwash intensity was 15 $L/(m^2\,s)$ and the air backwash period was 2 min. Air and water surface wash intensity was 15 and 4 $L/(m^2\,s)$, respectively, and the backwash period was 3 min. Only water intensity was 8 $L/(m^2\,s)$ and backwash period was 5 min. Water surface wash intensity was 3 $L/(m^2\,s)$, period time was 1 min. Long handle filter knobs of

DN25 were arranged on the filter plate, and 24 long handle filter knobs were arranged on each filter plate. Homogeneous filter media of single layer of quartz sand was used, and its effective size was $D = 0.9$–1.2 mm, nonuniformity factor was $K_{80} = 1.20$ (D80/D10), filter media thickness was 120 mm. Medium coarse sands were utilized on supporting layer, whose particle size was 2–4 mm and thickness was 100 mm.

5.3.5. Clear water pond

The adjusted volume of clear water pond was 6,000 m^3. Two groups of clear water ponds were designed, and each designed parameters was as follows: The effective volume was 3,000 m^3, the effective depth was 3.8 m, and the plane size was 28.6 m × 28.6 m. Ultrasonic liquid level transmitter was designed to control the water level in clear water pond.

5.3.6. The second pumping station

Pumping station was semi-underground frame structure, and its plane size was 17.00 m × 8.24 m. Water supply capacity of pumping station was $3.0 \times 10^4\ m^3/d$. Three large pumps (including one stand-by pump) and three small pumps were arranged at pumping station. The flow of large pump was 660 m^3/h, the pump lift was 49.0 m, and the motor power was 110 KW. The flow of small pump was 360 m^3/h, the pump lift was 45.0 m, and the motor power was 75 KW. Three backwash pumps (including one stand-by pump) were designed in filter, the pump flow was 750 m^3/h, the pump lift was 13.0 m, and motor power was 45 KW. The pressure of treated water was 0.45 MPa. In order to reduce power consumption, frequency control device was used to run in automatic way.

6. Conclusion

Aeration-lime softening-conventional water treatment process had positive effect on turbidity, total hardness, total iron and total dissolved solids removal. The process conditions were identified by the study of experiment, including milk of lime dosage was 140 mg/L, dosage of PAC was 8 mg/L, mixing speed was 300 r/min and mixing time was 2 min, flocculation speed was 50 r/min and flocculation time was 10 min followed by 10 min sediment. Treated water was filtered through 0.45-μm membrane, and all water quality indexes reached the limiting value of "Standards for drinking water quality" (GB5749-2006).

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