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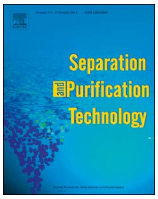

Electrochemical water softening using air-scoured washing for scale detachment

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ABSTRACT

Treatment of recirculate cooling water using electrochemical method has obtained great attentions in recent years due to its environmental friendliness and easy operation. In order to ensure persistent hardness removal efficiency, periodical cleaning of cathode surface is essential. However, currently available electrode cleaning techniques are either inefficient or laborious. In this work, air-scoured washing was proposed to replace conventional scale detachment methods in the electrochemical water softening process. Mirror stainless steel was found to be the most suitable cathode material because it could enhance scale detachment significantly. Effective water softening and scale detachment were achieved. The precipitation rate was as high as 25.5–34.3 g/h/m^2. After the air-scoured washing scale detachment, the cathode could resume their ability to soften. The energy consumption and the total removal efficiency were 17.6–22.3 kWh/kg $CaCO_3$ and 12.2–15.2%, respectively. Repetitive experimental results indicated the electrochemical water softening process using air-scoured washing could run steadily without any performance decay detected after repetitive operation.

1. Introduction

Evaporative cooling is broadly used in many industrial applications, such as electric power generation, petrochemical industry and steel manufacturing [1–3]. Recirculate cooling water usually contains high concentration of hardness ions including calcium and magnesium ions which may cause the scale formation on the surfaces of the heat transfer [4–9], and hence reduce the heat transfer efficiency in heat exchangers and plug the pipeline [10–14]. Many technologies have been developed and used for scale prevention. Adding anti-scalant is the most commonly utilized way in scale control application. In despite of satisfactory efficacy, it usually leads to contamination of the water source due to the foreign ions introduced by anti-scalant itself [15,16]. With the development of membrane technology, reverse osmosis (RO) is gradually becoming an effective process for water softening [17]. But this process still has some drawbacks. The membrane used is prone to mineral scale fouling because calcium and magnesium ions are chemically inclined to precipitate on the membrane surface [18–21], leading to a decrease in hardness removal efficiency and an increase in the energy consumption [22]. Furthermore, it also suffers from the problem that the concentrated water needs secondary disposal before it can be discharged.

Electrochemical treatment in hardness ions removal has attracted great attentions in recent years due to its environmental compatibility and versatility [23–29]. The basic principle of the electrochemical water softening (EWS) process is to create high concentration of hydroxide ions in the vicinity of the cathode by the chemical reactions Eqs. (1) and (2):

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{1}$$

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2\uparrow \tag{2}$$

The hydroxide ions would play an essential role in harness ions removal by the reactions Eqs. (3)–(5):

$$OH^- + HCO_3^- = CO_3^{2-} + H_2O \tag{3}$$

$$Ca^{2+} + CO_3^{2-} = CaCO_3\downarrow \tag{4}$$

$$Mg^{2+} + 2OH^- = Mg(OH)_2\downarrow \tag{5}$$

These insolubility reaction products adhere to the cathode and form a precipitate film, which is recognized as a scale layer. When the cathode surface is totally covered by the scale, cathode deactivation would occur. Therefore, it is necessary to clean cathode surface periodically to guarantee the effluent quality.

The most widespread used cathode cleaning method is the mechanical scraping [30]. It has been used for decades in scale detachment

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due to its easy operation. The scale layer is removed by moving the elastic scraper periodically from top to the bottom of the circular shaped cathode surface. However, since the elastic scraper occupies large space, the installation of the elastic scraper between the anodes and cathodes would inevitably increase the electrodes distance. This not only lowers the effective cathode area leading to a decrease in hardness removal efficiency, but also gives rise to overly high energy consumption.

Other important methods such as polarity reversal and acid washing are well known to be effective ways to remove scale [31,32]. Nevertheless, they also exhibit plenty of shortcomings. Polarity reversal leads to a reduction in electrode lifetime dramatically [31]. Acid washing consumes a large amount of hazardous chemical substances with strong erosive property, and produces wastewater that requires neutralization. In addition, it demands plenty of auxiliary facilities for chemical reagents storage, which is costly and non-environmentally friendly. Ultrasonic has been considered as an alternative technique recently [33,34]. Generally, ultrasonic produces vibrations in a certain frequency that could create pressure waves in the water and consequently cavitation effects which lead to continuous scale detachment from the cathode. Although ultrasonic has many advantages including satisfactory efficacy and environmental friendliness, it also suffers from some harsh problems, such as complicated configuration, difficulty in maintenance and expensive investment. If scale deposits can be detached greenly and conveniently, the economic and environmental benefits will be bettered substantially.

In this work, we proposed and tested a new scale detachment method called air-scoured washing. Air scour has been widely applied in filters backwashing [35]. Disperse bubbles produce tremendous turbulence and buoyancy in water. Besides, powerful shear stress will be released when bubbles incline to break up near the water surface [36]. Therefore, air-scoured washing can be a promising method for scale detachment. It has many advantages including simple configuration, easy operation, and environmental friendliness. The advantages and drawbacks of each scale detachment technique mentioned above are summarized in Table 1. The major objectives of this study are to select the proper cathode, to investigate the softening as well as detachment performance in an operational cycle, and to evaluate the operational stability of the electrochemical water softening process.

2. Materials and method

2.1. Experimental setup

The experimental setup is schematically shown in Fig. 1. The reactor has a working volume of 100 mL. A DSA sheet anode with dimension of 21 × 7 × 2 cm and a cathode with the same area were fixed in the reactor. An insulated silicone spacer was placed between the electrodes to keep an electrode gap of 5 mm. A sedimentation tank was used to separate the suspended solids in the effluent. A reservoir was used to store the circulation solution, and the solution temperature was maintained at 25 °C using a water bath.

2.1.1. Procedures for proper cathode selection

In this process, different cathodes were used. The main properties of the cathodes are presented in Table 2. In order to calculate the accumulation of the calcium removal accurately, the electrochemical reactor was operated in a batch mode, including a water softening step and a scale detachment step. During the softening step, the solution was circulated at a flow rate of 10 L/h upward through the reactor with valves 4 and 5 being opened and the others being closed; current density was controlled at 100 A/m^2. During detachment step, valves 3, 4 and 5 were open, while others were closed; the solution and bubbles entered the reactor through the valves 4 and 3, respectively, and come out through valve 5.

2.1.2. Procedures for single pass water softening and detachment

A mirror stainless steel was served as the cathode. The electrochemical reactor was also operated in a batch mode, including a water softening step and a scale detachment step. In the water softening step, valves 1 and 2 were open, while valves 3, 4 and 5 were closed; feed water entered the system through valve 1 and passed the electrochemical reactor upward. At the same time, DC electricity was supplied to the electrochemical reactor and the effluent came out through the valve 2. The gases generated at the electrodes were taken away by the stream through valve 2. The scale detachment step started when the time interval reached a certain value. During this stage, valves 1, 2 and 3 were open, while valves 4 and 5 were closed; feed water and bubbles passed through the reactor upward simultaneously entered from the valves 1 and 3, respectively. The effluent came out through the valve 2.

Table 1
Summarization of the advantages and drawbacks of scale detachment techniques.

Scale detachment techniques name	Advantages	Drawbacks
Mechanical scraping	Easy operation	Low softening efficiency and overly high energy consumption
Polarity reversal	Simple configuration	Costly and non-environmentally friendly
Acid washing	High detachment efficiency	Reduce electrode lifetime dramatically
Ultrasonic	Satisfactory detachment efficacy and environmental friendliness	Complicated configuration, difficulty in maintenance and expensive investment
Air-scoured washing	Simple configuration, easy operation, and environmental friendliness	Require air supply system

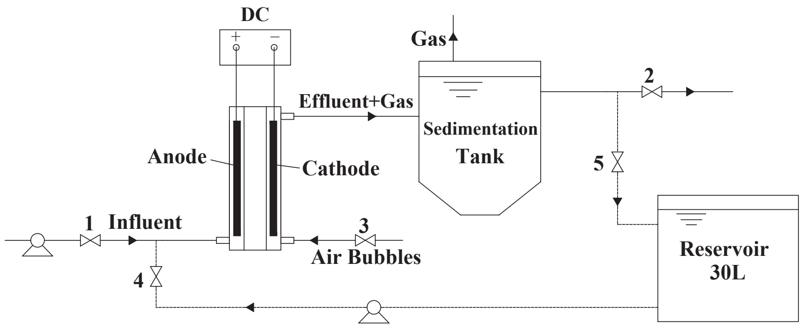

Fig. 1. Experimental setup.