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Pressurized electro-dewatering of activated sludge: Analysis of electrode configurations (anode)

Zengjun Yang [a], Xuebin Lu [a,e,*], Shuting Zhang [a], Keqiang Zhang [b], Suli Zhi [b], Haigang Guo [c], Qian Li [a], Xiaoyan Yu [d]

[a] School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[b] Agro-environmental Protection Institute, Ministry of Agriculture, Tianjin 300191, China
[c] Achievement Transformation Center, Hebei University of Engineering, Handan 056038, China
[d] School of Energy and Chemical Engineering, Liaoning Technical University, Hu Ludao 125105, China
[e] Department of Chemistry and Environmental Science, School of Science, Tibet University, Lhasa 850000, China

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ABSTRACT

An electric field and mechanical pressure combined are considered an effective electro-dewatering (PED) technology for activated sludge. Here, the curved surface anodes were used for electro-dewatering to improve the effective anode area, and the PED characteristics were investigated for three anode types (flat plate, sawtooth plate and wave plate). First, evaluation methodology of the modified energy consumption (W'^{filt}_{ED}) and the modified processing capacity (Q'^{filt}_{ED} and Q'^{filt}_{CRO}) were established, with electro-dewatering factor (ξ_{ED}), to evaluate the PED efficiency of different anode configurations under three raw sludge processing capacity modes. Second, the solid content distribution was analyzed by the layered method, and the electric field and current density distribution were analyzed by the finite element method. Finally, the gas emission mechanism of the curved surface anodes was discussed. When the raw sludge processing capacity and dewatering time (10 min) were the same, nearly the same extent of dewatering was achieved for the wave plate anode as for the flat plate anode. The total filtrate amount was 69.5 g and 59.0 g for the wave plate and flat plate anodes, respectively, and Q'^{filt}_{CRO} increased by 17.8% for the former. Under the same raw sludge thickness, the dewatering percentages in area A of the sawtooth plate and wave plate anodes were 10% and 11%, respectively, higher than that of the flat plate anode. However, according to numeric simulation results, the current density at the tips of the sawtooth plate anode can reach 740–770 A/m^2, which can reduce its service life as compared to flat plate anode. In area D, gas was more easily emitted from the wave plate anode than from the flat plate anode, reducing the influence of the gas barrier layer on the electrical contact between the sludge cake and the anode.

1. Introduction

Increasing quantities of sewage sludge from industry and cities pose a major societal problem due to high processing costs and more restrictive environmental regulations. Sewage sludge contains a large quantity of water, which is difficult to remove by mechanical dewatering (MD) alone (Citeau et al., 2012b). Electrically assisted MD, known as electro-dewatering (ED), is an alternative emerging technology for energy-efficient liquid/solids separation in the dewatering of sewage sludge (Mahmoud et al., 2016) and can increase solids content up to 70 wt% (Saveyn et al., 2006), while requiring less energy than thermal drying techniques. In numerous experiments and several engineering approaches, the most widely used method of ED technology involves a combination of mechanical pressure and electric fields (PED) (Weber and Stahl, 2002; Feng et al., 2014). PED has been characterized by the following benefits: first, mechanical pressure causes sludge cakes to closely contact the anode; second, mechanical pressure causes water to rapidly flow from the filter medium (Gazbar et al., 1994); third, the gas layer is compressed to reduce the contact resistance (Larue and Vorobiev, 2004; Larue et al., 2006; Mahmoud et al., 2010; Tuan et al., 2012).

However, certain existing problems inhibit widespread commercialization of PED, and few reports have described its commercial application. On one hand, PED requires corrosion-resistant electrodes, which are costly (Mahmoud et al., 2010). On the other

* Corresponding author at: School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China.

E-mail address: xbltju@tju.edu.cn (X. Lu).

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hand, relatively good dewatering could be achieved many ways (Miller et al., 1998; Mahmoud et al., 2010, 2011, 2016), but in industrial applications, more attention should be paid to the capacity and stability. Additionally, a drying layer on the anode side occurs later in the PED step (Navab-Daneshmand et al., 2015; Conrardy et al., 2016; Citeau et al., 2012a, 2012b, 2015), resulting in reduced energy efficiency, and the thickness of the sludge cake is therefore limited.

Increasing the electrochemically reactive anode area could improve the processing capacity. Mahmoud et al. (2016) introduced the PED process productivity equation, and pointed out that laboratory productivity will always be higher than pilot or commercial scale, because in the latter, back-wash at the end of the cycle and filling time would also be included; Zhang et al. (2017) modified the PED process productivity equation, which was verified through commercial operations. However, the PED process productivity equation was based on flat plate anodes, which were easy to produce an electrically insulating layer due to the formation of gas barrier (Mahmoud et al., 2010, 2018), especially in engineering applications which cannot achieve a high mechanical pressure (Snyman et al., 2000; Raats et al., 2002; Hwang and Min, 2003).

The dimensionally stable anodes (DSA), which was mainly titanium matrix coated with mixed metal oxide layer (MMO), usually was a flat plate (Yu et al., 2010; Mahmoud et al., 2011; Navab-Daneshmand et al., 2012; Yoshida et al., 2013; Feng et al., 2014; Qian et al., 2015; Conrardy et al., 2016; Zhang et al., 2017; Li et al., 2018) or a grid-like structure (Citeau et al., 2012a, 2012b, 2015; Desabres et al., 2016, 2017) in previous studies. Some researchers applied corona or linear anodes, but mechanical pressure was not easily applied (Lamont-Black et al., 2015; Tao et al., 2015; Deng et al., 2016). Compared to a flat plate anode, a grid-like DSA can help gas emission of oxygen evolution reaction, but requires a filter medium to prevent sludge from being discharged from the pores of the anode. However, special attention should be paid to the choice of a filter medium: as it was pointed out by Saveyn et al. (2006) and Citeau et al. (2012b, 2015), filter medium with high electrical resistance can significantly increase the electrical energy consumption, when it is placed between the sludge cake and the anode. Therefore, both improving the effective anode reaction area and finding effective exhaust measures are the key to the widespread use of PED technology. With the improvement of DSA manufacturing technologies, nonplanar DSAs can be used as ED anodes. In this paper, the wave plate and the sawtooth plate anodes as well as the traditional flat plate anode were used to investigate the PED characteristics of activated sludge.

2. Materials and methods

2.1. Sludge

Activated sludge samples were taken after centrifugal dewatering units from Tianjin Xianyang Road wastewater treatment plant in China. This plant treats the mixed sewage, which originated from 47% of municipal sewage and 53% of industrial sewage (mainly printing and dyeing, pulp and paper, and motor industries). The physicochemical characteristics of the sludge are listed in Table 1. The sludge was transported to the laboratory and stored at 4 °C before use, and all the tests were completed within a week.

Table 1
Physicochemical characteristics of the activated sludge.

Parameters	Measured values	Method
Dryness	79.9 ± 0.3% w/w	105 °C, 24 h, oven
Volatile solids	48.7 ± 0.1% w/w	500 °C, 1 h, muffle
pH	7.2 ± 0.3	pH meter
Zeta potential	−27.5 to −21.3 mV	Zeta potential meter
Conductivity	1.1 ± 0.2 mS/cm	Conductivity meter

2.2. Experimental setup

A PED test system is shown schematically in Fig. 1. It consisted of a compressive piston moving in a cylinder (model: SCJ80 × 75–50) and an electro-dewatering compartment of sludge loaded. The pressure applied to the removable piston is controlled by compressed air at the top of the unit. The cross area of the loading compartment was 10 cm × 10 cm. There is a seal cover made of plexiglass above the loading compartment, and the seal cover located 50 μm distance from anode was used to prevent the sludge being extruded from sides and the discharge of the gas generated by the anode reaction. The gas during PED processes was collected by a rubber seal between the top of the seal cover and the piston shaft, and its volume was measured by a gas flowmeter (minimum scale:10 ml, LML-1).

The upper square anode is inserted against the piston head made of titanium coated with IrO_2-Ta_2O_5 to prevent its corrosion (Ir/Ta ratio: 2.2, sintering temperature: 500 °C, coating thickness: 10 μm, MAGNETO special anodes co., LTD, Suzhou city, China). Three different configurations of anode (flat, sawtooth and wave) were investigated, respectively, and the geometric parameters of the anodes were shown in detail in Fig. 1. The effective area of the flat anode (S_f), sawtooth anode ($S_s \approx 1.13S_f$), and wave anode ($S_w \approx 1.18S_f$) was 100 cm^2, 113.4 cm^2, and 118.1 cm^2, respectively, and the raw sludge processing volume were written as follows: $V_f = S_f \times H_f$ (flat anode), $V_s = S_f \times H_s + 2.2S_f$ (sawtooth anode) and $V_w = S_f \times H_w + 2.2S_f$ (wave anode) with the corresponding thickness of sludge cake (H_f for the flat, H_s for the sawtooth and H_w for the wave). The lower cathode made of belt-type 80 mesh stainless steel (AISI 316L) lies under a 250 mesh thinner filter cloth (0.01 cm in thickness) producing the voltage drop negligibly. The anode was set to contact the top surface of the sludge cake, and a constant pressure (100 kPa) was applied immediately if electrical current started, ensuring a close electrical contact between the anode and sludge.

A DC power supply (maximum 50 V and 20 A, KXN-5020D) operating under constant voltage (U-PED, 20 V) was connected to the anode and cathode. Two thermocouples were used to monitor the temperature fluctuations near the anode and cathode, and the energy consumption was measured by a digital watt-hour meter. All experimental data were recorded over time by a computer visa the RS232 interface.

The average cake solids content of the whole bed during ED was calculated continuously from the recorded mass of the filtrate. The cake solids content of sludge sample was determined as follows:

$$S_t = \frac{m_0(1-w)}{m_0 - m_t} \quad (1)$$

where m_0 is the initial mass of sludge dewatered, m_t is the mass of filtrate collected at t time, w is the initial water content of sludge dewatered and was measured by drying at 105 °C during 24 h.

The cake solids content for different layers was measured by drying at 105 °C during 24 h at the end of each run. A new run was started for each dewatering time. Here a new method of sludge cake layered was proposed by cutting the hump of fixed height, as shown in Fig. 2. After ED, the sludge cake was placed into several square frames (thickness of 0.05 cm, AISI 304), and each square frames correspond to a certain thickness of sludge dewatered, that is 0.05 cm. When the frames were removed, the hump of fixed thickness was cut, and the sample was collected separately for moisture distribution tests. In previous studies, the filter