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A comparative study of electro-dewatering process performance for activated and digested wastewater sludge

Akrama Mahmoud [a,*], Andrew F.A. Hoadley [b], Morgane Citeau [c], Jean Michel Sorbet [a], Gelade Olivier [a], Jean Vaxelaire [a], Jérémy Olivier [a]

[a] Laboratoire de Thermique Energétique et Procédés (EAD 1932), UPPA, ENSGTI, BP 7511, 64075 Pau Cedex, France
[b] Department of Chemical Engineering, Building 35, Clayton Campus, Monash University, Victoria 3800, Australia
[c] OLEAD - 11 rue Monge, Parc Industriel Bersol 2, 33600 Pessac, France

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ABSTRACT

Electro-dewatering (EDW) is an alternative emerging and energy-efficient technology that provides improved liquid/solids separations in the dewatering of wastewater sludge. The EDW technology is not only an innovative dewatering method for significantly reducing the volume of wastewater sludge before re-utilization or disposal, but is also a promising emerging method which may potentially be used for decontamination purposes. In this study, the influence of the sludge properties (e.g. electrical conductivity, zeta potential, specific cake resistance, among others) on their mechanical and electrical behaviour in terms of dewaterability and electro-dewaterability, the applied current (current density from 20 to 80 A/m^2), and filter cloth position relative to the electrode was investigated. A two-sided filter press at lab-scale with moving anode was used, and the treatment performance of the EDW process on two different types of wastewater sludge (activated and digested) was thoroughly assessed from both an electrochemical viewpoint and in terms of the dewatering rate. The results showed that the conditioned digested sludge was more easily dewatered by mechanical dewatering (MDW) with 34–35% (w%) of dry solids content compared to 19–20% (w%) for the activated sludge, thanks to the lower content of both the microbial extracellular polymeric substances (EPS) and the volatile suspended solids fraction.

For the EDW results, the electrical conductivity of the sludge was pivotal to the dryness of the final solids and therefore also to the dewatering kinetics. The results demonstrated that the activated sludge arrived at an equilibrium much faster (after approximately 3600 s) compared with digested sludge, thanks to its lower electrical conductivity (0.8 mS/cm) providing a greater voltage drop across the cathode and therefore more repulsion of the solids from the cathode leading to continuously high filtrate flowrate. Also the EDW performance was analysed by comparing the ratio of the filtrate volume collected at the anode to the volume collected at the cathode side. For digested sludge at 5 bar, 40 A/m^2 different positions of the filter cloth were tested but these configurations barely impacted the EDW performance, despite having a significant impact on the energy requirements. At industrial scale, it would be useful to position the filter cloths at some distance from the electrodes, but this study shows that this benefit may be quickly outweighed by the loss in EDW energy efficiency.

1. Introduction

Over the last few decades, the volume of municipal and industrial sewage sludge has increased many times due to the intensification of water purification; and the cost of disposal of this sludge has increased due to more stringent legislation for the protection of the environment (Mahmoud et al., 2011a, 2013, 2016). Wastewater sludge is an important component of the product of wastewater treatment facilities. The sludge has to be dewatered and toxic or noxious contaminants, such as heavy metals, microorganisms and hazardous organics have to be removed, or inactivated, before re-use can be considered. Depending on the locality, sludge may be reused as a valuable soil amendment, composted, incinerated or disposed to landfill (Tuan and Sillanpää, 2010a; Mahmoud et al.,

* Corresponding author. Laboratoire de Thermique Energétique et Procédés (EAD 1932), UPPA, ENSGTI, rue Jules Ferry, BP 7511, 64075 Pau, France.
E-mail address: amahmoud@gmx.fr (A. Mahmoud).

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2011a, 2013). The residual water content in the sludge is usually removed by mechanical processes involving gravitational settlers, centrifuges, belt filter presses and plate and frame filter-presses, and further dried, if necessary, by conventional thermal drying. The dewatering efficiencies obtained with wastewater sludge are generally low, with a practical limit of around 35% (wt% solids on a wet basis) even when the sludge is conditioned before dewatering (Chen et al., 2002; Mahmoud et al., 2011a, 2016).

A traditional thermal drying process can achieve a high sludge dryness level and provide good control and high destruction of contaminants. However, the energy consumption is proportional to the amount of water, which must be evaporated, and both high capital and operating costs are proportional to the water removal from wastewater sludge (Mahmoud et al., 2008, 2016; Fytili and Zabaniotou, 2008). The minimum drying energy requirement refers to water vaporisation enthalpy of about 0.62 $kWh/kg_{water\ removed}$ and in industrial devices it can reach as high as 1.2 $kWh/kg_{water\ removed}$ (Gazbar et al., 1994; Perry and Green, 1997; Mujumdar, 2007; Mahmoud et al., 2008, 2010, 2011a, 2013). Depending on the type of wastewater sludge, the electro-dewatering (EDW) is considered as one of the most effective emerging processes for the improvement of wastewater sludge dewatering efficiency (Mahmoud et al., 2011a, 2013, 2016). In the EDW process, an electric field is applied during the conventional mechanical pressure dewatering (MDW) of the sludge to enhance the separation process efficiency with low energy consumption, to increase the final dry solids content and to accelerate the dewatering kinetics (Saveyn et al., 2005, 2006; Mahmoud et al., 2010, 2011a, 2013, 2016; Citeau et al., 2011, 2012a, 2016; Glendinning et al., 2010; Tuan et al., 2008, 2012a; Iwata et al., 2013; Olivier et al., 2014; Feng et al., 2014). Recent studies investigated a wide range of scenarios in order to reduce the water content, to optimize the operating mode for a desired final dry solids content and to obtain the best energetically and economically feasible EDW process. A number of these studies reported in literature are summarized in Table 1. Most of these studies are empirical and essentially focused on the process parameters and the sludge characteristics (Mahmoud et al., 2010, 2013), as shown in Table 1. The studies are grouped based on the mode of dewatering where U-EDW refers to constant voltage, I-EDW refers to constant current and E-EDW refers to constant electric field strength.

Recently, Mahmoud and co-workers compared the energy required to dewater and dry wastewater sludge for different combinations of either electrical or mechanical dewatering followed by thermal drying (Mahmoud et al., 2008, 2011a,b, 2013, 2016). They demonstrated that to achieve a dryness fraction of 50%, the optimum EDW process had an energy consumption of 0.30 kWh/kg of water removed, which is less than 50% of the energy consumption of a thermal drying process (Mahmoud et al., 2011a). They also reported that by delaying the application of the electric field to the filter cake compression stage, there was a potential saving in power consumption of around 10–12% in the case of U-EDW and about 30–46% in the case of I-EDW compared to the application of the electrical field from the start (Mahmoud et al., 2016). For their part, Citeau and co-workers with their new improvement in EDW process by anode flushing (anode filtrate recirculation) based on the work of Larue et al. (2001, 2006), showed that there was also a potential reduction in power consumption of around 12–19% in the case of I-EDW with anode flushing compared with no flushing to reach the same level in dryness of bentonite sludge (66.2% (wt%)) (Citeau et al., 2016).

In addition to its relative high dryness level and the energy-efficiency in the dewatering of wastewater sludge, EDW technology is also a potential method of reducing bacterial pathogens in wastewater sludge (Esmaeily et al., 2006; Huang et al., 2008; Navab-Daneshmand et al., 2012). They reported that the EDW process offered an interesting disinfection method for the reduction to below detection limits of *Salmonella* spp bacteria, enteric viruses and fecal coliforms (FC). In their experiments, Navab-Daneshmand et al. (2012) demonstrated that the principal source of total coliforms and *Escherichia coli* inactivation mechanisms during the EDW process was related to the significant temperature rise from Ohmic heating. This is also supported by the findings of Yin et al. (2018). Indeed, other studies pointed out that the EDW process may also be a potential method for decontaminating hazardous substances via the migration of heavy metals and organic compounds, such as oils and greases present in the sludge (Kim et al., 2002; Hwang and Min, 2003; Yang et al., 2005; Tuan et al., 2008, 2012a,b; Tuan and Sillanpää, 2010a,b; Mahmoud et al., 2010, 2011a; Xu et al., 2017; Xiao et al., 2017).

The colloidal particles in the wastewater sludge usually possess a negative surface charge, and therefore are surrounded by a layer with a higher density of positive charges, and this phenomenon is referred to as the electric double layer. When an electric field is applied, the usually negative charged particles move towards the electrode of the opposite charge. The water from pores and interstices, commonly with associated cations, is driven towards the negative electrode (Weber and Stahl, 2002, 2003; Yang et al., 2009; Mahmoud et al., 2010, 2011a). Ions species (anions and cations) are also subjected to electromigration transport according to their own ionic mobilities (Newman, 1991; Mahmoud et al., 2003, 2007, 2010; Mahmoud and Hoadley, 2012). The electro-kinetic transport phenomena (*ek*) involved in sludge electro-dewatering process includes the following phenomena: electrophoresis (*eph*), electro-osmosis (*eo*), electromigration (*em*), and electrolysis (Mahmoud et al., 2010, 2011a, 2013, 2016). Besides the electro-kinetic transport flow (*ekf*), there is also a hydraulic pressure driven flow (filtration and/or compression) (*pdf*) in the EDW process, as shown in Fig. 1. From this, the total transport flow in the EDW process, Q_{EDW}, is the sum of the flux generated by the pressure driving force (Q_{pdf}) and the flux generated by the electrical field driving force (Q_{ek}), as schematically depicted in Fig. 1.

The EDW process thus induces the migration of negatively charged organic matter present in the sludge (such as fatty acids, humus substances, among others) (Xiao et al., 2017). Heavy metals are also migrated in their various speciations: in both an abiotic form (e.g. soluble, adsorbed, exchangeable, precipitated, organically complexed, residual phases, among others) or biotic form (e.g. extracellular and intracellular species) (Kim et al., 2002; Hwang and Min, 2003; Tuan et al., 2008, 2012a,b; Tuan and Sillanpää, 2010a,b; Mahmoud et al., 2010, 2011a). As these toxic metals often limit the reuse of sludge in agriculture, any reduction in heavy metals could be extremely beneficial to protect the public health and the environment.

Hwang and Min (2003) observed a large reduction of the heavy metal concentration such as Zn, Mn, Pb, Cd, Ni in the sludge cake after an electro-dewatering run. Tuan and co-workers showed that concentration of Na^+ and K^+ were reduced by 51% and 78%, respectively in the sludge cake in comparison to experiments with only mechanical dewatering. Fe ions, Ca^{2+} and Mg^{2+} concentrations were found to be lower in sludge at the anode and higher at the cathode, while Cr concentrations were increased in the sludge cake and anode effluent (Tuan and Sillanpää, 2010a,b). In their investigation, Mahmoud et al. (2011a) reported that the EDW under high levels of applied voltage caused colouration and even odour of the water removed at the cathode side, giving it a dark green-brown appearance instead of grey colour. At high levels of voltage, they also observed an increase in the turbidity, electrical conductivity and the total suspended solids (TSS) of the water