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Treatment of oil sands produced water using combined electrocoagulation and chemical coagulation techniques

Laleh Shamaei [a], Behnam Khorshidi [a], Basil Perdicakis [b], Mohtada Sadrzadeh [a,*]

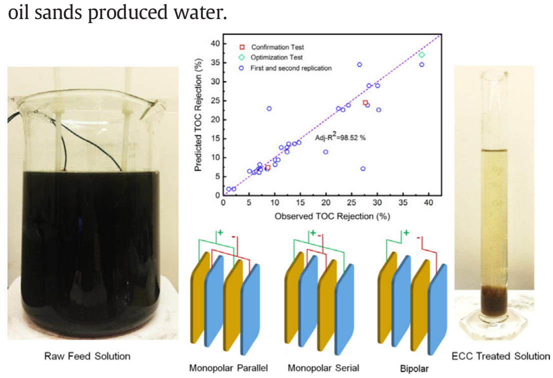
[a] Department of Mechanical Engineering, 10-367 Donadeo Innovation Center for Engineering, Advanced Water Research Lab (AWRL), University of Alberta, Edmonton T6G 1H9, AB, Canada
[b] Suncor Energy Inc., P.O. Box 2844, 150-6th Ave. SW, Calgary T2P 3E3, Alberta, Canada

HIGHLIGHTS

- ECC process was used for the first time for treatment of oil sands produced water.
- The synergistic effect of parameters on ECC performance was studied.
- The significant parameters on removal efficiency of the ECC were identified.
- ECC process was optimized and a model was proposed to predict removal efficiency.
- ECC process can be potentially used as a pretreatment method for membrane process.

GRAPHICAL ABSTRACT

The developed integrated electrocoagulation with chemical coagulation enables removing organic matter from oil sands produced water.



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ABSTRACT

Hybrid electrocoagulation-chemical coagulation (EC-CC) process has attracted a growing attention for the removal of various types of wastewaters contaminants. In this paper, the feasibility of EC-CC technique as an alternative to conventional chemical processes for the treatment of steam assisted gravity drainage (SAGD) produced water has been systematically studied. Eight parameters, namely electrode material, cell configuration, pH and temperature of the solution, chemical coagulant dosage, intensity of the electrical current, mixing rate, and treatment time were studied. To explore the synergistic effect of the design parameters, the experimental trials were arranged using Taguchi method. Analysis of variance (ANOVA) was performed to evaluate the effect of each design parameter on the organic matter removal from the SAGD produced water. It was found that all parameters except the electrode arrangement had a significant effect on the removal efficiency of the EC-CC process. Among these parameters, the chemical coagulant and the treatment time had the most significant contribution to the efficiency by 40% and 26%, respectively. The optimum condition for the highest TOC removal efficiency (39.8%) was obtained by applying 0.34 A to Al electrode in a bipolar (BP) configuration when the pH, temperature, coagulant concentration, mixing rate, and reaction time were set to 8, 60 °C, 200 mg/L, 700 rpm, and 90 min, respectively. Moreover, a second-order polynomial regression model was proposed to predict the removal efficiency in terms

Abbreviations: AC, Applied current; AM, Anode material; ANOVA, Analysis of variance; BFW, Boiler feed water; BOD, Biological oxygen demand; BP, Bipolar; C, Coagulant concentration; CC, Chemical coagulant; CCC, Critical coagulation concentration; COD, Chemical oxygen demand; DC, Direct current; DOE, Design of experiment; EC, Electrocoagulation; EF, Electroflotation; EC-CC, Electrocoagulation-chemical coagulation; FSS, Factor sum of square; MP-P, Monopolar - parallel; MP-S, Monopolar - serial; MR, Mixing rate; NOM, Natural organic matter; OFAT, One-factor-at-a-time; PI, Percentage of influence; SAGD, Steam assisted gravity drainage; Seq SS, Sequential sum of square; SN, Signal to noise; t, Time; T, Temperature; TOC, Total organic carbon; Total SS, Total sum of square; WLS, Warm lime softener.

* Corresponding author.
E-mail addresses: shamaeig@ualberta.ca (L. Shamaei), behnam@ualberta.ca (B. Khorshidi), bperdicakis@suncor.com (B. Perdicakis), sadrzade@ualberta.ca (M. Sadrzadeh).

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of design parameters. An excellent agreement between the model predictions and experimental data was obtained with the adjusted R^2 of about 99%.

1. Introduction

Steam-assisted gravity drainage (SAGD) produced water is the water returned from the bitumen or heavy oil reservoir. In the SAGD extraction process, steam is injected into the reservoir above a producer well to decrease the viscosity of the bitumen. A mixture of melted bitumen and water is pumped up through the production wells. The water resources for SAGD operation which are brackish in nature are groundwater aquifers near the extraction plants (Balsamo et al., 2014; Elsayed et al., 2015). Exploring more efficient methods for the treatment, recycle, and reuse of produced water is an active area of technology development interest for the resource extraction industry in Alberta, Canada.

Hybrid electrocoagulation-chemical coagulation (EC-CC) is an alternative water treatment process that benefits from the advantages of both chemical coagulation (CC) and electrocoagulation (EC) techniques (Chen, 2004; Sahu et al., 2014). CC is a popular additive-based water treatment process in which the addition of chemicals is required to destabilize and precipitate the dissolved and suspended materials (Bektaş, 2017; Moussa et al., 2017; Song et al., 2004). The additive nature of this process results in high amount of residual chemicals in the treated wastewater (Moussa et al., 2017; Song et al., 2004). EC is one of the most eco-friendly water treatment technologies that has been effectively applied for the removal of suspended matter from various types of wastewater (Secula et al., 2014; Emamjomeh and Sivakumar, 2009). In contrast to CC, EC involves in situ generation of coagulant species triggered by applying electric current through metal electrodes (Hakizimana et al., 2017; Bazrafshan et al., 2016). This technique is receiving growing attention due to its operational advantages over the conventional CC technique (Yousuf et al., 2001). In particular, the EC process allows precise control of production rate of coagulant species without generation of unnecessary byproducts (Zhu et al., 2005). However, EC technique suffers from two significant drawbacks: high energy consumption and the need to replace the sacrificial anodes after exhaustion (Tsouris et al., 2001; Barrera-Díaz et al., 2011). Regarding that, employing a hybrid EC-CC technique that integrates the strengths of both EC and CC techniques can potentially result in cost- and energy-efficient water purification process.

Possible chemical reactions in a batch EC reactor unit are presented in Fig. 1. During the EC process, the applied current promotes the dissolution reactions on the sacrificial anodes and generates metal cations and metal hydroxide ions in the solution (Vepsäläinen et al., 2012). These products destabilize the Boiler feed water (BFW) contaminants in the solution through mechanisms including charge neutralization, and precipitate enmeshment (Bratby, 2016). The metal ions can also reduce on the cathode surface (Vepsäläinen, 2012). The micrometer-sized hydrogen bubbles, produced by the reduction reactions on the cathode surfaces, will attach to the aggregated sludge and float them to the surface (Bockris et al., 2002; Vepsäläinen, 2012). This mechanism which is called electroflotation (EF) can significantly enhance the separation efficiency of EC unit (Wang et al., 2009; Kyzas and Matis, 2016). It has been reported that the combined EC-EF process provides several advantages over single EC technique (Kuokkanen, 2016; Ricordel et al., 2010). Primarily, the separation time and the water content of the generated sludge during the EC-EF process is significantly lower than that in EC process which is very beneficial for the sludge dewatering process (Moussa et al., 2017; Emamjomeh and Sivakumar, 2009; Qin et al., 2013). Furthermore, the operational costs of EC-EF process can significantly decrease by easy removal of the floated flocks and recovering the hydrogen produced during the process as a source of green energy (Ricordel et al., 2010; Vu et al., 2014; Phalakornkule et al., 2010; Ali and Yaakob, 2012).

Several attempts have been made to investigate the influence of chemical, electrical and operational conditions on the efficiency of the EC (Hakizimana et al., 2017; Asselin et al., 2008a; Vepsäläinen et al., 2011a; Holt et al., 2005; Ghosh et al., 2008; Hu et al., 2016; Al-Qodah and Al-Shannag, 2017; Al-Qodah et al., 2018). Investigation on the effect of electrode material on the treatment of slaughterhouse wastewater by EC process revealed that employing mild steel in a BP electrode configuration resulted in the highest removal efficiency for oil and biological oxygen demand (BOD) (Asselin et al., 2008b). However, using EC process to remove oxytetracycline hydrochloride from water showed that aluminum as anode material is more effective than iron (Nariyan et al., 2017a). In a parametric study on the reduction of chemical oxygen demand (COD) and color in livestock wastewater, it was found that the initial pH of the solution and the electrical current density are the most significant factors (yul Tak et al., 2015). The results of EC treatment of municipal wastewater showed that higher COD and nutrient removal efficiencies can be obtained by applying higher electrical voltage on the electrode system (Al-Shannag et al., 2013). Application of EC process to remove COD from baker's yeast wastewater also revealed that COD removal efficiency improved with increase of mixing rate (Al-Shannag et al., 2014). Another study on the application of EC process for the pretreatment of coal seam water to lower the scaling of reverse osmosis membranes reported that larger electric current density and longer contact time resulted in a higher removal of divalent salts from the solution (Millar et al., 2014). Similar results also were reported for the removal of metals from real mine water using EC technique (Nariyan et al., 2017b). Current density was found as a significant parameter for the application of EC process for removal of uranium from mine water using iron and aluminum as anode material (Nariyan et al., 2018). A study on the effect of electric charge per liter, initial pH and temperature on the removal of natural organic matter (NOM) from surface water indicated that temperature was almost insignificant in comparison to other two factors (Vazquez et al., 2014). The results of investigating the effects of current density, treatment time, and initial pH on the reduction of hardness, COD, and color from the produced water showed that initial pH and current density were the most significant factors on the efficiency of EC process (Zhao et al., 2014). Solution pH and current density were also found as significant factors for the EC treatment of highly stable calcareo-argillaceous colloids (Çırak, 2018).

Although the studies mentioned above approve the feasibility of EC process for the treatment of various types of wastewaters and provide valuable insight into the effect of individual parameters on EC performance, they would have been more informative if all the design factors had been investigated synergistically (Dean et al., 2017). In most of earlier studies, the one-factor-at-a-time (OFAT) method has been employed to study the effect of design parameters on EC removal efficiency. In the OFAT method, only the effect of one factor is investigated at a time during each experiment; therefore, it is not capable of assessing the synergistic effects of design factors (Czitrom, 2012; McGee et al., 2017).

In the present study, the feasibility of EC-CC process to remove organic material from SAGD produced water was evaluated. The goal was to analyze the effects of several operational parameters including anode material, pH and temperature of the solution (°C), coagulant concentration (mg/L), electrode configuration, applied current (A), mixing rate (rpm), and process time (min) on the EC-CC process. The experimental trials were designed using a fractional factorial design known