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Experimental studies on the enhanced performance of lightweight oil recovery using a combined electrocoagulation and magnetic field processes

Yang Liu, Jie Yang, Wenming Jiang*, Yimei Chen, Chaojiang Yang, Tianyu Wang, Yuxing Li

College of Pipeline and Civil Engineering, Shandong Provincial Key Laboratory of Oil & Gas Storage and Transportation Safety, China University of Petroleum, Qingdao, Shandong, China

H I G H L I G H T S

- The study on marine lightweight oil spill is urgent because of its explosion risk and contamination to environment.
- A combined electrocoagulation and magnetic field processes was investigated synthetically.
- Permanent magnet installed was proved to strengthen mass transfer process and reduce energy consumption
- The magnetic field strength of 40 mT was optimal.

A R T I C L E I N F O

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A B S T R A C T

On marine oil spill, inflammable lightweight oil has characteristics of explosion risk and contamination of marine enviroment, therefore treatment of stable emulsion with micron oil droplets is urgent. This study aimed to propose a combined electrocoagulation and magnetic field processes to enhance performance of lightweight oil recovery with lower energy consumption. The effects of current density, electrolysis time, strength and direction of magnetic field on the overall treatment efficiency of the reactor were explored. Furthermore, the comparison between coupling device and only electrocoagulation through tracking oil removal in nine regions between the electrodes. The results were shown that the permanent magnets applied was found to enhance demulsification process within electrocoagulation reactor. For a given current density of 60 A m^{-2} at 16 min, Lorentz force downward was proved to promote the sedimentation of coagulants. As the magnetic field strength increases from 20 to 60 mT, oil removal efficiency was observed to increase and then decrease, and simultaneously energy consumption reduced and then present constantly. The results were found that the magnetic field strength of 40 mT was optimal within electrocoagulation reactor, which can not only diminishe difference of mass transfer rate along the height of vertical plate but also consume lowest energy.

1. Introduction

Lightweight oil with a boiling point range of 350–420° centigree is discharged into the sea in large volume tending to be ignited easily on oil spills, due to human error associated with offshore petroleum production and transportation operations. The lightweight oil spilled is prone to drift and diffuse rapidly because of the smaller density and viscosity compared with crude oil, and thereby the O/W emulsion with sea water is formed under the agitation of sea current, tide, wind wave, etc. In the emulsion, stable oil droplets at the micron scale float on the surface of large sea area for long time. It not only cause the accident of explosion but also severely harmful to the enviroment. Aimed at the emulsifying, flammable and explosive nature of the lightweight oil is challenge of oil spill treatment, thus it is urgent to develop an efficient and environmentally friendly technology for lightweight oil spill treatment.

* Corresponding author.
E-mail addresses: liuyang82@upc.edu.cn (Y. Liu), 865651148@qq.com (J. Yang), jiangwenming@upc.edu.cn (W. Jiang), 2902854873@qq.com (Y. Chen), yangchaojiang2012@163.com (C. Yang), 602013778@qq.com (T. Wang), liyx@upc.edu.cn (Y. Li).

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Electrocoagulation (EC) processes has more recently been certified for treatment of stable emulsified oil droplets with micron grade. Compared with traditional technologies such as: adsorbents, flocculents, precipitation, ultrafilters, chemical addition, adsorption and membrane separation (Adhoum et al., 2004; Golder et al., 2007a, b; Akbal and Camci, 2010; Ren et al., 2015), the EC, characterized by reduced sludge production, no requirement of chemicals, and ease of operation without pH adjustment, is environmentally-friendly, competitive and effective technology under low reaction temperature conditions (Holt, 2003) (Liu, 2017). Furthermore, solar cells were verificated by experiment to provide adequate power successfully to EC process, which made this treatment technology possible to be adequate for emergency operation of lightweight oil spill on the sea (García-García et al., 2015).

In essence, an EC reactor is an electrochemical cell. Due to strong adsorption capacity or adhesion strength of aluminum coagulants, a large number of bubbles were found in aluminum flocs when microfracture characteristics of aluminum and iron flocs were compared. And consequently aluminum electrodes are proved to be more efficient than iron electrodes (Xu, 2016).

During electrolysis in emulsion treatment, the chemical reactions occurring as seen in Eqs. (1)–(4) (Holt, 2003).

For anode:

$$Al \text{ - } 3e \rightarrow Al^{3+} \; E^0{}_A = -1.66\,\text{V} \tag{1}$$

In addition, there is oxygen evolution reaction:

$$4OH^- \rightarrow O_2\uparrow + 2H_2O + 4e \; E^0{}_A = -0.40\,\text{V} \tag{2}$$

The reaction occurring at the cathode is dependent on pH, and at neutral or alkaline pH, hydrogen is produced:

$$2H_2O + 2e \rightarrow H_2\uparrow + 2OH^- \; E^0{}_C = -0.83\,\text{V} \tag{3}$$

At acidic conditions:

$$2H^+ + 2e \rightarrow H_2\uparrow \; E^0{}_C = 0\,\text{V} \tag{4}$$

As Eq. (1), a sacrificial metal anode, usually aluminum, used to supply ions into the emulsion (Chen, 2004). The generated Al^{3+} ions combine with water and OH^- ions to immediately undergo further spontaneous hydrolysis reactions to form various monomeric species as $Al(OH)^{2+}$, $Al(OH)_2^+$, and $Al(OH)_4^-$, polymeric species as $Al_2(OH)_2^{4+}$ and $Al_2(OH)^{5+}$, which finally transform into amorphous $Al(OH)_{3(s)}$ and less soluble species as Al_2O_3 in terms of many complicated processes (Holt et al., 2002).

Thus, in an EC process the coagulating ions are produced ‘in situ’ for breaking of emulsion, and demulsification mechanism which depends on factors such as pH and coagulant dosage (Ahmadi et al., 2013), may be summarized as two points (Karhu et al., 2012):

(i) The polymeric hydroxoaluminium cations neutralize the surface charged of surfactant molecules responsible for oil emulsion stability. As a results, the van der Waals attraction predominates, thus the neutralized oil droplets may collide with each other and then coalesce because of their Brownian movement.
(ii) The amorphous hydroxide precipitate $Al(OH)_{3(s)}$ which is characteristic of lattice-like structure, large surface areas and attractive electrical forces can generate sweep flocculation.

In addition, when direct current is applied to water through a pair of electrodes, the energy barrier is overcome, and water is electrolyzed (Yang, 2007). Thus, it could be obviously observed that the hydrogen bubbles evolved from the cathode (Eqs. (3)–(4)) (Holt, 2003). Oxygen bubbles evolution is also possible on the anode (Eq. (2)) (Mameri et al., 1998), although this was not detected by Przhegorlinskii et al. (1987)'s analysis. As Kemis et al. Reported, analysis of collected gas by chromatography revealed the exclusive presence of hydrogen (Khemis et al., 2006). These small bubbles attract the aggregated particles and float the flocculated pollutants to the surface through natural buoyancy.

With the ever growing need for low energy-consumption and quick recovery process to meet the increasingly stringent standards, a large number of researchers spent much energy improving the mass transfer process between the electrodes in EC reactor and inhibiting of passivation. For example, cell with array of horizontal cylindrical anodes was found to remove 99.8% mass of total oil (Fouad et al., 2009), which have a higher mixing efficiency and higher floating ability than the traditional vertical parallel plate cell. A novelty, rotational anode was employed for effective emulsion treatment, and a result was found that the performance of a cell with vertically oriented electrodes is superior to that of a cell with horizontal electrodes (Khalaf et al., 2016). A satisfied COD removal efficiency (92.8%) and low salinity (84 μS cm $^{-1}$) were obtained when an electrochemical process with three-dimensional multi-phase electrode may be applied to treat petroleum refinery wastewater (Yan et al., 2011). As reported (Pi et al., 2014), periodic polarity reversal of the electrodes has led to reductions in the impact of passivation. Even so, it must be admitted that these issues like poor mass transfer condition and passivation are still seen as a serious potential limitation for applications where a low-cost, low maintenance water treatment facility is required. With the strictness of emission directives, thus more sophisticated treatment without addition external energy is needed.

Fortunately, some studies conducted has been proven that, magnetic field (MF) which has overriding advantages of ecological purity, safety, simplicity and less operating costs, could enhance the purification effect of emulsion through permanent magnet imposed between anode and cathode in the EC reactor. Thus, coupling EC/MF processes is good alternatives for lightweight oil recovery. As reported (Ni’Am et al., 2006), this combined process with iron electrodes was found to improve suspended solid removal from wastewater compared to EC process alone. MF can improve technological characteristics of the water, such as: better salt solubility, kinetic changes in salt crystallization and accelerated colloidal coagulation. Furthermore, exposure to MF would lead to higher electro-kinetic movement among the colloid, which will significantly increase the probability of attracting particles to cloak with one another (Othman et al., 2001). However, there is a little previous literature on the recovery of lightweight oil with micron size by EC coupled MF. Besides the literature has not revealed any systematic evaluation of existing applications leading to an agreed set of guidelines suitable for the design/operation of new applications. This may be due to failure to fully appreciate that the enhanced performance of lightweight oil recovery using MF within an EC reactor.

In this work, in order to assess the enhanced performance of lightweight oil recovery with micron size efficiently and systematically, the oil removal from the emulsion in nine regions between anode and cathode within EC reactor divided uniformly between the electrodes was tracked. The study aims to investigate the effect of permanent magnetic field imposed on lightweight oil recovery from the seawater, the optimal experimental conditions (the strength and direction of MF) and study the oil removal and cost consumption of only EC reactor in the same condition. In the meantime the possible enhanced mechanism using permanent magnets for treating emulsified oil were discussed.