Evaluation of the hydrodynamics generated by agitation and electromagnetic field during the electrocoagulation of oil/water emulsion

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ABSTRACT

The performance of breaking oil/water emulsions using the electrocoagulation technique in the presence of a magnetic stirrer or an electromagnetic field (EMF) is reported. A batch electrochemical cell has been used with a simulated oil/water emulsion. Here, a vertical, flat plate Fe anode and stainless steel (SS) cathode were used in an array style. In this study, the effect of the rotation speed and the intensity of the electromagnetic field have been investigated. The main reason is to compare the effect of the hydrodynamic and the magneto hydrodynamic on breaking the oil/water emulsion. Results indicated that the hydrodynamic effect enhanced the removal rate of oil to some extent, and considerably reduced the energy consumption per each kg of oil removed (from $2.36\,kW\,h/kg_{oil}$ at 0 rpm to $1.46\,kW\,h/kg_{oil}$ at 300 rpm). Moreover, experiments also indicated that the application of electromagnetic field enhanced the oil separation in a relatively same manner. The best position of electromagnetic field is under the electrodes, where the corresponding arbitrary direction of the magnetic flux intensity is parallel to the surface of the electrodes. During the same time interval, the EMF enhances the oil removal percentage to be 94.8% compared to 72.4% without it. Accordingly, the application of the electromagnetic field in a continuous process would enhance the oil separation at relatively same power consumption.

1. Introduction

In Egypt, authorities set a strict legislations on food industries to recycle and minimize the wastewater. Such industries should meet the national standards of the wastewater disposal to the public sewage networks and main streams. Several commercial technologies are available to remove impurities from the effluents of food processing and oleo chemical industries. However, some food company's deal with technical issues escalated while attempting to reduce the oil contaminant load to downstream wastewater systems [1]. During processing steps, oil can form floating layer, stable, or unstable emulsion with water. Methods of Oil-water (O/W) de-emulsification includes chemical and mechanical techniques. Chemical coagulation is carried out primarily by adding salts such as ferric sulfate, or aluminum sulfate to the emulsion, followed by a precipitation reaction. However, this method produces massive sludge that results in disposal hitches. Conversely, the mechanical methods, such as ultrafiltration, have restricted use because of the fouling problem of the membranes [2].

Recently, the electrochemical technique has regained importance because the researchers succeeded to decrease the energy consumption and enhance the contaminant removal from wastewater [2–4]. Usually, the electrochemical techniques are subdivided into two methods; electrooxidation and electrocoagulation (EC). The treatment of wastewater from food industry by electro-oxidation was carried out using different electrochemical cells to remove glucose and oil using either rotating anode, or two plate electrodes [5,6].

Generally speaking, the EC process is recognized as fast, instantaneous and in-situ process for the removal of pollutants. It has the merits of a compact unit size, simple operation, and low fixed and running costs. Basically, the EC produces an in-situ metal hydroxide coagulant, which trigger the formation of OH^- ion and H_2 gas at the cathode. Typically, the metal hydroxide traps the contaminants by several mechanisms. While the bubbles of the hydrogen gas attaches to some oil emulsions and move upward [7]. The main challenge to enhance the EC process is to increase the rate of oxidation of iron anode. One possible way is by decreasing the resistance boundary layer adjacent to the anode. This is done by rotating the fluid by a mixer, a magnetic stirrer, or a jet stream. However, these methods have limited application because of the difficulties of scaling up the process.

The term magneto hydrodynamics (MHD) is generally understood

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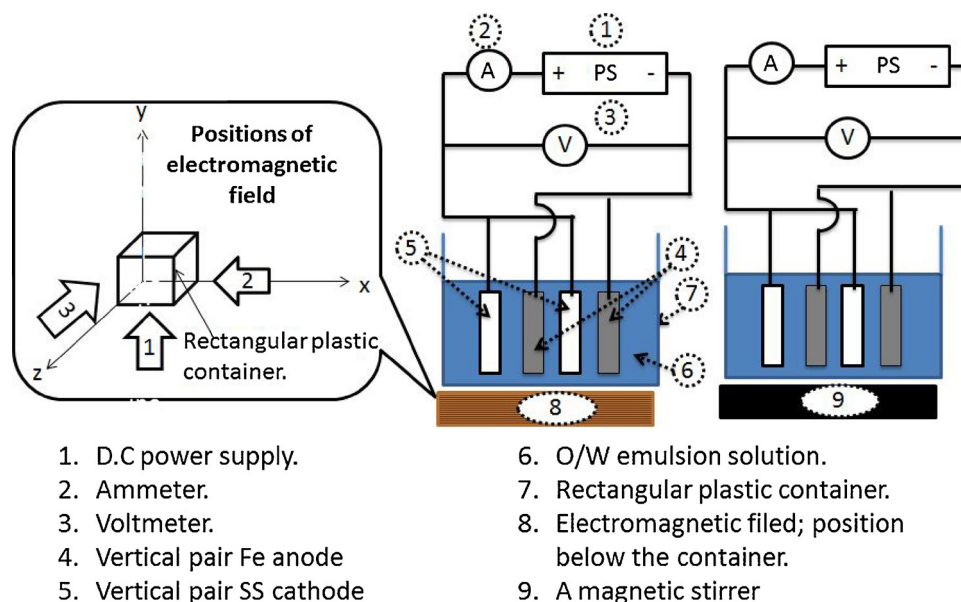E-mail address: m.salah.m@mu.edu.eg (M.S. Mahmoud).

Fig. 1. Schematic diagram of the experimental setup for single electrodes (Fe-SS), and double pair electrodes (Fe-SS/Fe-SS).

1. D.C power supply.
2. Ammeter.
3. Voltmeter.
4. Vertical pair Fe anode
5. Vertical pair SS cathode
6. O/W emulsion solution.
7. Rectangular plastic container.
8. Electromagnetic filed; position below the container.
9. A magnetic stirrer

meaning the application of electromagnetic field (EMF) to induce the movement of the ions [8]. The main mechanism of MHD is that the paramagnetic ions are induced by the magnetic flux imposed by the EMF. Many works are devoted to study the effect of the EMF on electrochemical reactions [9–12], particularly emphasizing on the enhancement of mass transfer during the process.

To speed up the EC process, iron ions should move from the layer adjacent to the anode to the bulk of wastewater. The movement of ions in EC process can be improved by rotating the solution or by using a magnetic field. Nevertheless, There is insufficient research on the dominant process among these two techniques to draw any firm conclusions about their effectiveness. This study is an attempt to address the issue of illustrating the difference between the gross fluid motion and the superimposed motion by EMF on the electrocoagulation process. Under the present process configuration, the optimum operating parameters for EC have been previously studied [12,13] and will be fixed in this study.

2. Experimental

The electrochemical cell displayed schematically in Fig. 1 consists of a rectangular acrylic container, with a dimension of (L × W × H = 0.1 × 0.07 × 0.15 m). Stainless steel (SS) plates, with dimensions of (L × W × thickness = 0.08 × 0.06 × 0.002 m), have been used as the cathode. Sacrificing Fe anodes, with same dimensions, are placed in the cell parallel to the cathodes. According to previous studies [12,13], the distance between each electrode pair was fixed at 0.015 m. The electrical setup consists of a 16 V DC power supply (BK PRECISION®), rheostat to adjust the current intensity and switch. An ammeter is connected in series to measure the current. Similarly, a voltammeter was connected in parallel to measure the voltage. All the experiments were performed at 25 ± 1 °C and at pH = 7 [14]. In the EMF experiments, a DC current passes through copper wire ($d_w = 0.35 \times 10^{-3}$ m) made as solenoid (800 turns) around an iron core ($d_c = 0.1$ m). Hence, a uniform magnetic field is generated. The magnetic field intensity caused by a steady current I is calculated from the Biot-Savart equation [15]:

$$B = \frac{\mu_o I}{4\pi} \int_{wire} \frac{dl \times \hat{r}}{r^2}$$

(1)

where the integral is calculated over the length of the solenoid wire,

and vector $d\ell$ is the vector line element with the same direction of the current I, μ_0 is the magnetic constant, r the distance between the location of $d\ell$ and the location where the magnetic field is intended, and $\hat{r}$ is a unit vector in the direction of r. For long wire, Eq. (1) becomes:

$$B = \frac{\mu I}{2\pi r}$$

(2)

Consequently, the EMF is generated through the iron core with a direction identified by the right-hand rule. Three different positions of the EMF have been investigated as shown in Fig. 1: (1) below the electrochemical cell; (2) beside the electrochemical cell, but parallel to the plates; and (3) beside the electrochemical cell, but perpendicular to the long side of the plates. The O/W emulsion was prepared by mixing the commercial-grade oil (50% sunflower, 50% soybean) with water containing NaCl (6 g/l) and 5 wt% of the emulsifying agent (Polyoxyethylene Sorbitan monolaurate, Tween® 20 obtained from Sigma Aldrich). Before each run, the cell was filled with 800 ml of the emulsion. Sampling procedure is done by taking 10 ml from the bulk of the emulsion every 10 min, analyzing it, and returning it back to the cell. A turbidity meter (Model TU-2016, LUTRON ELECTRONIC ENTERPRISE) is used to measure the oil concentration in the sample [16]. Initially, a calibration curve (turbidity vs. oil concentration) was used to detect the oil concentration as shown in Fig. 2. The percentage of oil removal is calculated by:

$$\% \, oil \, removal \, (from \, emulsion) = \frac{c_o - c_{(t)}}{c_o} \times 100$$

(3)

where c_o and $c_{(t)}$ are the concentrations (ml/l) at the beginning of the experiment and after time t (min), respectively.

To calculate the power consumption of the EC experiments, the current intensity and the voltage were measured. Therefore, the total energy consumption is calculated as follows:

$$Energy \, consumption \left(\frac{kWh}{kg_{oil}} \right) = \left[\frac{EIt}{60\rho(c_o - c_{(t)})V} \right]_{cell} + \left[\frac{EIt \times 10^{-3}}{60} \right]_{stirrer \, or \, EMF}$$

(4)

for the first term; E is the EC cell voltage (V), I is cell current (A), t is time for removal of 90% of oil (min), c_o and $c_{(t)}$ are the initial oil concentration, and the oil concentration at time t (ml/l), ρ is the solution density (g/ml), and V is the treated volume (l). For the second term