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Comparison of performance of continuous-flow and batch electrocoagulators: A case study for eliminating reactive blue 21 using iron electrodes

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ABSTRACT

A batch electrocoagulator was developed for optimal removal of reactive blue 21 from wastewater. The data from the batch reactor were then used to develop a continuous-flow reactor with similar performance for reduction of chemical oxygen demand (COD) and color removal. In the 1.8-L batch system, COD removal of 90% and color removal of 95% were achieved using a current density of 30 A/m^2, electrode area of 0.10 m^2, and electrocoagulation time of 7 min. The continuous-flow electrocoagulator consisted of two hollow iron tubes put together in a concentric configuration with a working volume of 1.5 L and an effective electrode area of 0.15 m^2. By keeping the current density and the applied electric charge the same in both the batch and the continuous-flow systems, the COD and color removals and energy consumption of both systems were the same within 10%. However, the color and COD removals by the batch reactor were higher than those of the continuous-flow electrocoagulator because the distribution of electroactive species in the batch reactor was more effective than that in the tube-in-tube electrocoagulator.

1. Introduction

A major challenge for sustainable development is the treatment of wastewater from industrial processes and the reuse of the treated water so that the processes generate zero wastes. There is an urgent need to develop more effective and inexpensive techniques for wastewater treatment. Among the evolving technologies, electrocoagulation is one that has received attention from the scientific community in the last decade [1,2]. The electrocoagulation process is widely accepted to produce less sludge than the conventional coagulation process [3]. From the point of view of sustainable development, electrocoagulation is environmentally friendly because the process does not produce secondary pollutants in the water such as sulfate or chloride ions [4]. In addition, the energy source for the process can be a solar photovoltaic panel that converts solar energy into direct current electricity [5,6]. Furthermore, it is also possible to reduce the energy consumption of the electrocoagulation system by harvesting the hydrogen produced during the treatment [7].

The textile industry produces considerable amounts of dye-containing wastewater during its dyeing and finishing operations. Dye-containing effluent is toxic to the environment since dyes are stable compounds that have low biodegradability and can be carcinogenic [8]. Many studies have reported that electrocoagulation has high efficiency in decolorization with the color removal ranging between 98% and 100% in most cases. A number of specific dyestuffs have been investigated, e.g. orange II [9], acid orange 7 [10], acid yellow 36 and 23 [11,12], reactive yellow 84 [13], acid red 14 [14], reactive black 5 [15], direct red 23 [16], acid red 2 [17], acid green 50 [18], crystal violet [19], acid blue 29, reactive red 2, acid red 97, reactive blue 4 [20], reactive blue 140 [21], reactive blue 29 [22], reactive orange 84 [23] and real wastewater containing dyes [24–27]. In both batch and continuous flow reactors, the decolorization efficiency has been found to depend on the initial pH, the dye concentration, and the applied current density. Further, in batch mode, the efficiency has been found to depend on the electrolysis time, and in continuous flow reactors, on the flow rate [2]. However, the promising

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laboratory results are still far from commercial success because most of the published articles on dye removal by electrocoagulation are mainly focused on the optimization of operating parameters in batch reactors. In articles that do describe continuous reactor experiments [16,21,28,29], there have been very few attempts to discuss the application of fundamental data from batch experiments to the design of continuous reactors.

The aim of the research discussed in this paper was to use experimental data from a batch electrocoagulator to develop and test the performance of a continuous-flow tube-in-tube electrocoagulator. First, the conditions necessary for establishing the connection between batch and continuous electrocoagulators are discussed. Secondly, batch experiments are described that were conducted to find fundamental data such as optimal current density and electrolysis (electrocoagulation) time, amounts of electric charge applied, and fluid flow behavior. Then, continuous-flow experiments are described that were designed using the proposed conditions and the experimental batch data. Reactive blue 21 was used as the model compound for the study of color removal in both the batch and the continuous-flow systems. Finally, the similarities and differences in the performances of the batch and the continuous-flow electrocoagulators are analyzed.

2. Conditions for establishing the connection between batch and continuous electrocoagulators

Conditions necessary for using experimental data from a batch electrocoagulator to develop a continuous-flow electrocoagulator are proposed as follows:

2.1. The electrode materials are the same in the batch and the continuous-flow reactors. This condition is required because characteristics of flocs generated by the reduction–oxidation reactions vary with types of the electrode materials especially the anodic material.

2.2. Distance between anode and cathode (inter-electrode distance or electrode gap) are the same in the batch and the continuous-flow reactors. This condition is required because the electrostatic field depends on the distance between the anode and the cathode. The distance between the electrodes affect the rates of collisions of the generated metal hydroxides [30,31], and thus it influences rates of dye removal. In addition, the distance between the electrodes influences the travel time of the generated ions from the electrode surface to the bulk solution, and thus it also affects energy consumption of the process [32].

2.3. The current densities are the same in both batch and continuous-flow operations. That is,

$$[j]\text{batch} = [j]\text{continuous}. \tag{1}$$

This condition is required because current density influences the production rates of metal ions, hydroxides and gas bubbles. The parameter controls both the reaction rate of an electrochemical process as well as the growth of flocs [1,33,34].

2.4. The amounts of metal ions released from the anode per liquid volume to be treated are the same in both the batch and the continuous-flow systems. That is,

$$\left[\frac{jS_A t}{V}\right]\text{batch} = \left[\frac{jS_A t}{V}\right]\text{continuous} = \left[\frac{jS_A}{Q}\right]\text{continuous}. \tag{2}$$

where j represents the current density, A/m^2; S_A represents the total electrode area, m^2; t represents the electrocoagulation time, min; V represents the effective volume, m^3; and Q represents the volumetric flow rate, m^3/min. This condition is required to ensure the same concentrations of the active species are achieved in both systems as the amount of electric charge applied controls the total amount of reactions taking place during the electrocoagulation treatment. For the continuous-flow electrocoagulator, the hydraulic retention time of the liquid in the effective volume (t_{HRT}) is given by:

$$t_{\text{electrocoagulation}} = t_{HRT} = \frac{V}{Q}. \tag{3}$$

2.5. The ratios of convective to diffusive mass transport in the batch and the continuous-flow reactors should be the same because the parameter describes the distribution of metal ions and hydroxides in the bulk solution. The distribution of metal ions and hydroxides in the bulk solution is related to the patterns of fluid flow in the systems.

2.6. Other operating parameters, such as arrangement of electrodes and type of power supply, are designed to be the same in the batch and the continuous-flow reactors.

2.7. Sedimentation processes that follow the electrocoagulation treatments are the same for the batch and the continuous experiments.

3. Materials and method

3.1. Synthetic wastewater

A blue reactive dye (reactive blue 21) supplied from a textile industry in Thailand was used to prepare synthetic wastewater by dissolving 500 mg/L of dye into tap water and adjusting pH with NaOH to 8.3 ± 0.1 and conductivity with NaCl to 2 mS/cm. Reactive blue 21 belongs to the phthalocyanine class and its chemical structure is shown in Fig. 1. An initial concentration of 500 mg/L was selected because it provided a chemical oxygen demand (COD) value of the same order of magnitude as that of actual wastewater from a textile factory. The values of pH and conductivity were selected to represent the upper bound pH and the lower bound conductivity of the textile wastewater, respectively.

3.2. Reactor configurations

Batchwise and continuous-flow electrocoagulators were studied in this research. The batch system consisted of a DC power supply, a power control and measurement units, an electrochemical reactor and a magnetic stirrer (Fig. 2a). The electrochemical reactor was a 2-L beaker with a set of five pairs of iron electrodes with a total area of 1011 cm^2. Each electrode had a circular shape with a diameter of 12.2 cm, three round holes for fluid transport with a diameter of 1.2 cm, four round holes for supporting rods with a diameter of 1.2 cm, a square hole with a side length of 2 cm for the cathode connection and a round hole with a diameter of 0.6 cm for the anode connection. The electrodes were connected vertically with a gap of 8.0 mm between electrodes. The magnetic stirrer bar was 3.9 cm long and 0.8 cm in diameter and was located at the bottom of the batch reactor. The electrodes were connected to the DC power supply in monopolar mode and the electrochemical reactor was operated in batch and galvanostatic mode.

As shown in Fig. 2b, the continuous-flow system consisted of a cylindrical tube with an effective volume of 1.5 L, an electrode assembly, a feed pump and a DC power supply unit. A hollow iron tube with a diameter of 3.2 cm and a length of 100 cm was used as the cathode, and a hollow iron tube with a diameter of 5.1 cm and a length of 100 cm was used as the anode. The electrodes were assembled in a concentric configuration with a gap of 7.5 mm between the inner surface of the anode and the outer surface of the cathode. The anode was attached to the top flange of the