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Controlling Water Temperature during the Electrocoagulation Process Using an Innovative Flow Column-Electrocoagulation Reactor

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Abstract**—**A flow column has been innovatively used in the design of a new electrocoagulation reactor (ECR1) that will reduce the temperature of water being treated; where the flow columns work as a radiator for the water being treated. In order to investigate the performance of ECR1 and compare it to that of traditional reactors; 600 mL water samples with an initial temperature of 35^{0}C were pumped continuously through these reactors for 30 min at current density of 1 mA/cm^2. The temperature of water being treated was measured at 5 minutes intervals over a 30 minutes period using a thermometer. Additional experiments were commenced to investigate the effects of initial temperature (15-35^{0}C), water conductivity (0.15 – 1.2 S) and current density (0.5 -3 mA/cm^2) on the performance of ECR1.

The results obtained demonstrated that the ECR1, at a current density of 1 mA/cm^2 and continuous flow model, reduced water temperature from 35^{0}C to the vicinity of 28^{0}C during the first 15 minutes and kept the same level till the end of the treatment time. While, the temperature increased from 28.1 to 29.8^{0}C and from 29.8 to 31.9^{0}C in the batch and the traditional continuous flow models respectively. In term of initial temperature**,** ECR1 maintained the temperature of water being treated within the range of 22 to 28^{0}C without the need for external cooling system even when the initial temperatures varied over a wide range (15 to 35^{0}C). The influent water conductivity was found to be a significant variable that affect the temperature. The desirable value of water conductivity is 0.6 S. However, it was found that the water temperature increased rapidly with a higher current density.

Keywords**—**Water temperature, flow column, electrocoagulation.

NOMENCLATURE

EC	Electrocoagulation	E	Conductivity
^{0}C	Celsius	Q	Generated heat
S	Siemens	I	Current
i	Current density	T	Temperature
R	Electrical resistance		

I. INTRODUCTION

ELECTROCOAGULATION technology defined as a treatment process for water and wastewater relies on the formation of coagulating ions by applying direct electrical current to metallic electrodes without adding traditional coagulants such as alum [1]-[3]. The generated coagulants will flocculate pollutants in the media being treated. In spite of having acknowledged the advantages of the electrocoagulation (EC) techniques to remove a wide range of pollutants such as phenols, heavy metals, and bacteria, from waters and wastewaters, its efficiency is limited by several operational parameters (such as electrolysis time, current density, electrode material, and solution temperature) [4]-[7]. One of these important parameters is the temperature which greatly affects the generation rate of hydroxyl radicals, dissolving of electrodes, and solubility of the precipitates [8], [9]. Some researchers investigated the effects of water temperature on the removal efficiency of different pollutants such as fluoride and dyes [10], [11]. However, the effect of temperature on EC performance has been studied insufficiently during the last century [12]. Moreover, this technology still has a deficiency in reactor design [13]. Thus, the present work represents a trial to fill a part of this gap by suggesting a new design of (ECR1) that utilizes the concept of evaporative in perforated-plate of flow columns (which are widely used in the chemical industries) to control the water temperature.

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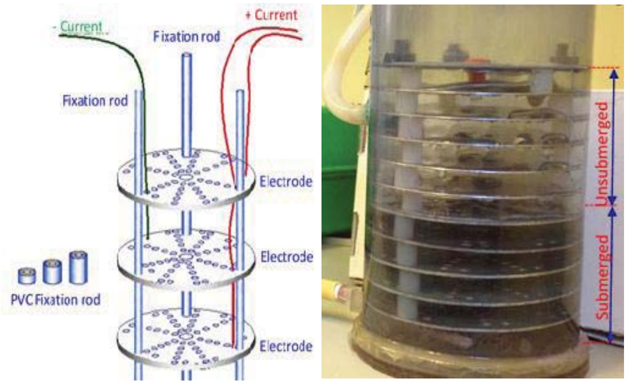
II. MATERIALS AND METHOD

A. Electrocoagulation Reactor

In this study, a new cylindrical reactor (ECR1) has been used. This reactor consists of a Perspex tube (25 cm in height and 10.5 cm in diameter) with a controllable working volume of 0.5 up to 1 L. The flow column consists of perforated discoid electrodes that are made from aluminum with a diameter of 10.4 cm (Fig. 1).

These perforated electrodes were vertically installed inside the reactor; each electrode was offset horizontally by an angle of 22.5 degrees from the one above it. This is to ensure that the water will follow a convoluted path to increase the contact time between water drops and the ambient air, enhancing evaporation which reduces water temperature. These electrodes have been held in the required position inside the reactor by using three PVC supporting rods and PVC fixation tubes (1cm in height) to maintain the required distance between electrodes. Aluminum was selected as the electrode material because of its cost effectiveness, ready availability, and lower oxidation potential [5], but it can be replaced by other materials depending on the targeted pollutant. A peristaltic pump (Watson Marlow type, model: 504U) was used to pump the water being treated through the reactor. A water bath (Clifton) used to adjust the temperature of water samples at the desire value. This reactor was supplied with a thermometer (Hanna; Model: HI 98130) to measure the temperature.

For comparison, a traditional batch and continuous flow reactors have been used in this study. The unsubmerged disks of ECR1 were removed to use them as a batch reactor (and without circulating water being treated). While, the traditional continuous flow model was performed by removing the unsubmerged disks of ECR1and allow the water to flow continuously thought this reactor for 30 minutes.



(a) Flow column (b) Reactor set up

Fig. 1 The New Reactor ECR1

B. Experimental Protocol

Initially, in order to estimate the performance of ECR1 and compare it to other traditional reactors, 600 mL water samples with a controlled initial temperature (35 ^{0}C) were pumped continuously into the new reactor using the peristaltic pump for 30 minutes at 1 mA/cm^2. At the same time, water samples with identical properties were treated by a traditional batch and continuous flow reactors. Water level inside the reactor was maintained up to the mid-height of the reactor in order to allow the perforated electrodes in the upper part (unsubmerged) to work as water diffuser. These unsubmerged electrodes converted the mass water flow into droplets that increase the contact area between water being treated with the ambient air, and consequently reduce water temperature. This self-cooling process makes the new reactor a cost effective alternative for the traditional reactors as the old EC reactors circulates water through an external cooler such as those in the studies of [14], [15].

The effect of three operational parameters, which are the initial temperature, water conductivity, and current density, on the performance of ECR1 was investigated as well. A water bath (type: Clifton) used to adjust the initial temperature of water samples at 20, 25, 30, and 35^{0}C, and an ice bath was used for the temperature of 15^{0}C. The desire value of water conductivity (0.15 to 0.6 S) was adjusted by using stoichiometric quantities of NaCl salt. A regulated direct current supplied from a rectifier (HQ Power; Model: PS 3010, 0-10 A, 0–30 V), current density can be changed according to the required electrical load (0.5–3 mA/cm^2). All experiments were repeated twice to ensure the reliability.

III. Results and Discussion

A. Effect of Flow Column on the Performance of EC Reactor

Performance of ECR1, in term of temperature control, was evaluated by treating 600 mL water samples with an initial temperature of 35^{0}C at current density of 1 mA/cm^2 for 30 minutes. Additionally, two models, traditional batch and continuous models were used to compare the results. The obtained results, Fig. 2, showed that ECR1 reduced water temperature from 35 to 27.3^{0}C during the first 5 minutes, then it increased gradually to the vicinity of 28^{0}C after 15 minutes and kept the same level till the end of the experiment. In the batch reactor model, the temperature decreases at the beginning to 29.8^{0}C and then continued to increase to reach 31.9^{0}C by the end of treatment period. Similarly, the traditional continues model initially reduced the temperature to 28.1^{0}C and then showed an increasing trend to reach 29.8^{0}C after 30 minutes.

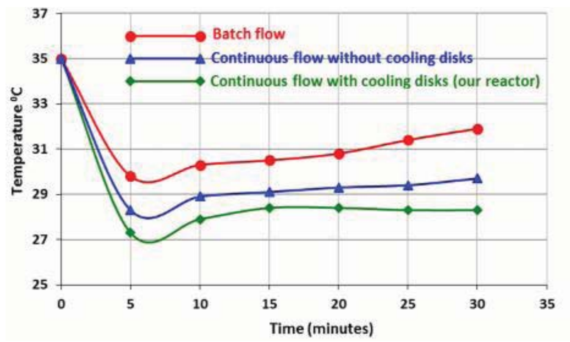


Fig. 2 Comparison among the Studied Reactors in Term of Temperature Behavior (i= 1mA/cm^2 and E= 0.15 S)

The temperature sharply decreased, to 27.3^{0}C, during the first 5 minutes due to the effect of the ambient temperature which was 21 to 22^{0}C, then it slightly increased to vicinity of 28^{0}C due to the effect of the applied current. Unlike the other reactors, ECR1 was able to keep the temperature of water being treated almost constant, about 28^{0}C, due to the shower – flow pattern that generated by the flow column. The water flow through these perforated electrodes dispersed the tap water being treated into small drops that increased the contacted area (superficial area) between water drops and the ambient air, and consequently cool down the water being treated.

B. Effect of Initial Temperature

Effect of initial temperature on the performance of ECR1 was investigated by treating water samples with different initial temperatures (15, 20, 25, 30, and 35^{0}C) for 30 minutes. The obtained results showed that ECR1 was able to decrease the temperature of water being treated, after 30 m, from 30 and 35^{0}C to 28.1 and 28.3^{0}C respectively. While lower temperatures, 25, 20 and 15^{0}C, increased slowly to reach 27, 25, and 22.1^{0}C respectively. These results, Fig. 2, show that ECR1 maintained the temperature of water being treated within the range of 22 to 28^{0}C without the need for external cooling system even when the initial temperatures varied over a wide range (15 to 35^{0}C). Reduction the need for external cooling systems, due to the effect of flow column, makes ECR1 an economic and effective alternative for the traditional reactors; especially to treat pollutants that required moderate treatment temperature.

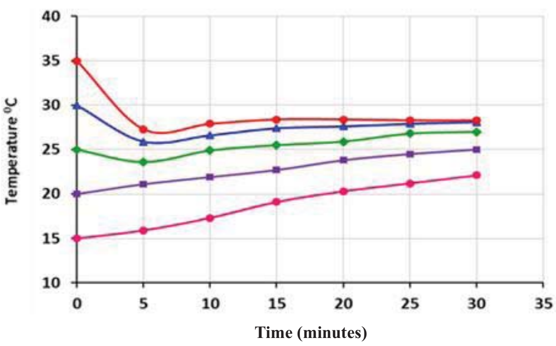


Fig. 3 Effect of Initial Temperature on ECR1 Performance (i= 1mA/cm^2 and E= 0.15 S).

C. Effect of water Conductivity (Electrolyte Concentration)

According to the principle of joule heating (ohmic heating), passing of electric currents through solution will heat it due to the electrical resistance [16]. The generated heat can be calculated according to [17]:

$$Q = R \,.\, I^2 \tag{1}$$

where Q is the generated heat; R is the electrical resistance; and I is current. Hence, the conductivity of water being treated plays a key role in temperature generation as it facilitates the passage of current. In order to investigate the effect of water conductivity on temperature generation inside ECR1 at 1 mA/cm^2, water samples with conductivity of 0.15, 0.3, 0.6, and 1.2 S were prepared by adding stoichiometric amounts of NaCl to tap water. These samples were treated at 1 mA/cm^2 for 20 min. The obtained results, Fig. 4, showed a clear decrease in water temperature as the conductivity increased from 0.15 to 0.3 and 0.6 S, but it brought a negligible change when the conductivity become greater than 0.6 S . Water temperature decreased from 23.8 to 21.4 and 20.3 ^{0}C as the conductivity increased from 0.15 to 0.3 and 0.6 S respectively. However, increasing water conductivity from 0.6 to 1.2 S merely reduced water temperature by 0.3 ^{0}C. Thus, in this investigation, it might be reasonable to infer that the water conductivity of 0.6 S is the optimum value.

D. Effect of Current Density

As it mentioned before, according to the principle of joule heating, the magnitude of electric current significantly effects the temperature of solutions which passing through. For an initial temperature of 20^{0}C and a conductivity of 0.6 S, the influence of current density on the temperature of water being treated was investigated at 0.5, 1.0, 2.0, and 3.0 mA/cm^2. Water temperature rapidly increased as current density increased. It was found that water temperature increased from 20^{0}C to 20.1, 20.3, 21.4, and 23.2^{0}C as the current density increased to 0.5, 1, 2, and 3 mA/cm^2 respectively, Fig. 5. These results confirm that ECR1 can maintain the temperature of water, at conductivity of 0.6 S, within the range of 20 to 25^{0}C even when the applied current density reaches 3 mA/cm^2. This makes ECR1 a promising alternative for traditional reactors to treat a wide range of pollutants that required low treatment temperature.

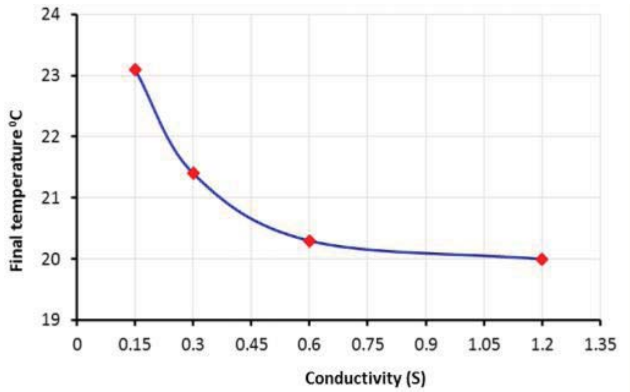


Fig. 4 Effect of water conductivity on water temperature (i= 1mA/cm^2, T =20 min)

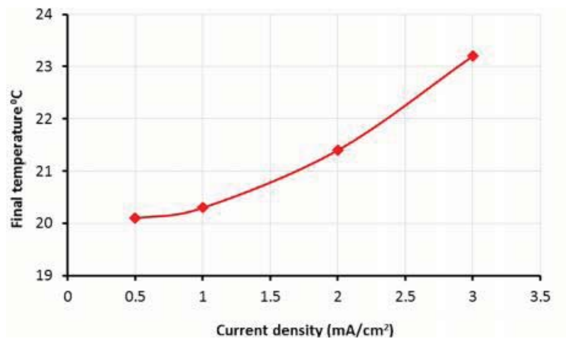


Fig. 5 Effect of Current Density on Water Temperature (conductivity = 0.6 S, T =20 min)

The ability of this innovative reactor to reduce water temperature and keep it at a certain level without the need for an external cooling system makes it an economic and effective alternative for the traditional reactors; especially to treat pollutants that required moderate treatment temperature. For instance, water defluoridation was studied at wide range of temperature (20 to 50^{0}C) and found that the optimum fluoride removal accord at ambient temperature [10]. It has been found that the removal of acid Red 14 from wastewater decreased as the temperature increased higher than 300 K (27^{0}C) [11]. Chemical oxygen (COD) removal from mechanical polishing wastewater was investigated at 15 up to 35C^0 and found that the optimum temperature was 25C^0 [18]. It was found that the removal both of sulfate and COD, from petroleum refinery wastewater, at 25^{0}C better than that at 40^{0}C [19]. A study about polyvinyl alcohol removal from water samples at temperature range between 288 and 318 K (15 to 45^{0}C), indicated that the best indium ion removal efficiency was achieved at 298 K (25^{0}C) [20]. Removal of oil from biofuel wastewater has been investigated at 20 and 50^{0}C, better removal efficiency was obtained at lower temperatures [21].

IV. Conclusion

The performance of the new closed batch electrocoagulation reactor ECR1 has been investigated regards to water temperature control. The results showed that the ECR1 has the ability to reduce the temperature of water being treated from 35 to about 28 ^{0}C within the first 15 minutes of treatment and kept the same level till the end of treatment time. In contrast, the other types of reactors reduced the temperature during the first 5 minutes of treatment due to the effect of ambient air and then showed an increasing tendency for the rest time of treatment. In general, the performance of ECR1 can be enhanced significantly by increasing water conductivity. While increasing the current density cause a noticeable increment in water temperature. In general, at conductivity of 0.6 S, ECR1 has the ability to keep the temperature of water being treated around the room temperature even when the current density reaches 3 mA/cm^2.

It is worthy to note that the need for an external cooling system (such as glass-cooling spiral) has been reduced and compensated by the flow column.

In conclusion, the obtained results demonstrated that the new reactor ECR1 can be used effectively and economically to treat a wide range of pollutants; especially those pollutants that required a moderate treatment temperatures (such as fluoride, sulfate, and trivalent chromium Cr (III)). Future work will include further optimization of the whole process to increase efficiency.

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