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Electrocoagulation process in water treatment: A review of electrocoagulation modeling approaches

Jean Nepo Hakizimana [a,f], Bouchaib Gourich [a,*], Mohammed Chafi [a], Youssef Stiriba [b], Christophe Vial [c,d], Patrick Drogui [e], Jamal Naja [f]

[a] Laboratoire d'Environnement, Procédés et Energie, Ecole Supérieure de Technologie, Université Hassan II de Casablanca, Route d'El Jadida, km 7, BP 8012, Oasis Casablanca, Morocco
[b] ETSEQ, Departament d'Enginyeria Mecanica, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain
[c] Université Clermont Auvergne, Université Blaise Pascal, Institut Pascal, BP 10448, F-63000 Clermont-Ferrand, France
[d] CNRS, UMR 6602, IP, F-63178 Aubière, France
[e] Laboratoire d'Electrotechnologies Environnementales et Procédés Oxydatifs (LEEPO), Centre Eau Terre Environnement, Institut National de la Recherche Scientifique (INRS), 490, rue de la Couronne, Québec (Québec) G1K 9A9, Canada
[f] Chimie Appliquée et Environnement, Faculté des Sciences et Techniques Settat, B.P 577 Route de Casablanca, Morocco

HIGHLIGHTS

- Electrocoagulation is a versatile process able to treat drinking and waste waters.
- The pros and cons of electrocoagulation (EC) are compared to alternative processes.
- EC suffers from a lack of scale-up methodology and the current models are reviewed.
- Four challenges emerge, covering theoretical, modeling and techno-economic aspects.
- Outlooks for future research and developments are suggested.

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ABSTRACT

Electrocoagulation process (EC) has been the subject of several reviews in the last decade, and is still a very active area of research. Most published works deals with applications for treatment of drinking water and urban, industrial or agricultural wastewaters so as to enhance the simultaneous abatement of soluble and colloidal pollution. These also include contributions to theoretical understanding, electrode materials, operating conditions, reactor design and even techno-economic analysis. Even though, the numerous advantages reported in the literature, and the pros and cons of EC in comparison to alternative processes, its industrial application is not yet considered as an established wastewater technology because of the lack of systematic models for reactor scale-up. This paper presents a comprehensive review on its development and design. The most recent advances on EC reactor modeling are summarized with special emphasis on four major issues that still constitute the cornerstone of EC: the theoretical understanding of mechanisms governing pollution abatement, modeling approaches, CFD simulations, and techno-economic optimization. Finally, outlooks for future research and developments are suggested.

Contents

* Corresponding author.
E-mail address: gourichgp@hotmail.com (B. Gourich).

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1. Introduction

Preservation of water resources is one of the 21st century's biggest challenges. It has to face several issues, which among them are: population growth, deforestation, rapid urbanization, industrialization and warming global climate change [1]. Nowadays, the access to safe drinking water is limited and under stress; water pollution may seriously impact aquatic ecosystems and the availability of healthy freshwater. Therefore, there is a need to develop efficient technologies and approaches for treating and managing wastewaters, to maintain quality and improve quantity at large scale while ensuring environmental protection and sustainability, for instance urban, industrial and agricultural wastewaters. More robust efficient drinking water treatments are also required to deal with risks posed by environmental contamination, for example presence of nitrate or fluoride ions at high concentrations.

The EC process can be used for the treatment of drinking water and wastewater. EC consists of generating coagulant species in situ by electrolytic oxidation of sacrificial anode materials triggered by electric current applied through the electrodes. The metal ions generated by electrochemical dissolution of a consumable anode spontaneously undergo hydrolysis in water, depending on the pH, forming various coagulant species including hydroxide precipitates (able to remove pollutants by adsorption/settling) and other ions metal species. Al and Fe materials are the most commonly used as electrode materials thanks to various advantages: their availability, i.e. abundance on the earth and low price, their non-toxicity, as iron and aluminum hydroxides formed by precipitation are relatively non-toxic, and their high valence that leads to an efficient removal of pollutant. Besides, simultaneous cathodic reaction allows for pollutant removal either by deposition on cathode electrode or by flotation (evolution of hydrogen at the cathode). The anode and the cathode are usually made of the same metal, although electrodissolution should occur only at the anode. EC can be conducted as a batch or continuous process. The large extent of its applications has been recently reviewed by Emamjomeh and Sivakumar [2] and more recently by Kabdaşlı et al. [3]. EC is an old process, as old as electricity [3]. The use of EC in drinking water treatment plants was reported in the 19th century in England and wastewater treatment plants operated in the USA in the beginning of the 20th century [4]. At the end of the 30s, it had been mainly replaced by chemical coagulation and by biological treatments for the abatement of colloidal and soluble organic pollutions in wastewater, respectively. The main reason was the higher operating cost, in particular the price of electricity in this period. The situation has, of course, drastically changed and the advantages of EC have been "rediscovered" since the 90s. Mollah et al. [5] have reported 10 advantages that have been, more or less, assessed in the literature. These can be summarized in Table 1, with the specific drawbacks of EC in comparison to alternative treatments. EC presents also other issues than cited in Table 1, for example the need for sludge handling, but chemical coagulation and activated sludge process have to address the same issue. In practice, the composition of EC sludge is close to that obtained using chemical coagulation when either alum or ferric chloride are used, which means that sludge disposal should be similar. Conversely, a specific issue of EC is that, to the best of our knowledge, there are unfortunately almost no comprehensive reviews of EC modeling and scale-up approaches for water treatment.

The aim of this work is, therefore, to summarize, discuss and analyze recent advances on modeling approaches developed for the simulation and the scale-up of EC operation. We start first by describing various mechanisms for pollution abatement. Then, the key operation parameters and reactor design attributes will be discussed so as to introduce the details of modeling aspects. Later, the main methodologies and design strategies will be reviewed from a critical point of view and linked to the techno-economic analysis of the EC process. Finally, some outlooks for future research and developments will be suggested.

2. Theoretical background on electrocoagulation process

Electrocoagulation combines various mechanisms that can be electrochemical (metal dissolution and water reduction, pollutant electro-oxidation or electro-reduction…), chemical (acid/base equilibria with pH change, hydroxide precipitation, redox reaction in the bulk…) and physical (physical adsorption, coagulation, flotation…). These can be sequential and/or parallel. All of them are summarized in Fig. 1 which highlights the complexity and the interplay between the mechanisms of EC process. These mechanisms are detailed below.

Table 1
The advantages and disadvantages of the EC process.

Advantages	Disadvantages
Nonspecific method	Need for maintenance
Address drinking water and wastewater	
Combines oxidation, coagulation and precipitation (results in lower capital costs [5])	Electrode passivation over time
Reduced need for chemical reagents (replaced by either Al or Fe electrodes and electricity)	Need for high-conductivity water
Reduced operating cost	
Reduced risk of secondary pollution	
Low sludge production	Lack of systematic reactor design [4]
Without moving parts	
Low energy requirements	
Solar power can be used	