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Research article

Performance analysis of a continuous serpentine flow reactor for electrochemical oxidation of synthetic and real textile wastewater: Energy consumption, mass transfer coefficient and economic analysis

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ABSTRACT

A continuous flow electrochemical reactor was developed, and its application was tested for the treatment of textile wastewater. A parallel plate configuration with serpentine flow was chosen for the continuous flow reactor. Uniparameter optimization was carried out for electrochemical oxidation of synthetic and real textile wastewater (collected from the inlet of the effluent treatment plant). Chemical Oxygen Demand (COD) removal efficiency of 90% was achieved for synthetic textile wastewater (initial COD - 780 mg L^{-1}) at a flow rate of 500 mL h^{-1} (retention time of 6 h) and a current density of 1.15 mA cm^{-2} and the energy consumption for the degradation was 9.2 kWh (kg COD)$^{-1}$. The complete degradation of real textile wastewater (initial COD of 368 mg L^{-1}) was obtained at a current density of 1.15 mA cm^{-2}, NaCl concentration of 1 g L^{-1} and retention time of 6 h. Energy consumption and mass transfer coefficient of the reactions were calculated. The continuous flow reactor performed better than batch reactor with reference to energy consumption and economy. The overall treatment cost for complete COD removal of real textile wastewater was 5.83 USD m^{-3}.

1. Introduction

Application of electrochemical oxidation for the treatment of a variety of wastewater is well established (Fernandes et al., 2015; Martínez-Huitle et al., 2015; Pillai and Gupta, 2016a, 2015a; Pillai et al., 2015; Rodrigo et al., 2014; Sirés and Brillas, 2012). Among the various electrode materials, lead dioxide coated on mild steel has proven to be effective for degradation of dyes and phenol (Pillai and Gupta, 2015a, 2015b; Pillai et al., 2015). The oxidation mainly proceeds through the action of hydroxyl radical, which concentrates in a small layer near the electrode surface (Pereira et al., 2012). Hence, for the treatment of large quantity of wastewater, a large surface area of the electrode is required to overcome the mass transfer limitations. Another viable option is the use of active oxidants (active chlorine species being the most popular) and/or the use of flow reactors (Pereira et al., 2012). Ling et al. have suggested the application of continuous flow reactors to overcome the issues of mass transfer limitations and inadequate treatment efficiencies in batch reactors (Ling et al., 2015).

Various types of continuous flow reactors are studied including the tubular reactor, baffled reactor, plunger flow reactor, continuous stirred tank reactor and so on (Körbahti and Tanyolaç, 2009; Ling et al., 2015; Zhu et al., 2015). Plug flow reactors were chosen as an alternative to overcome the inefficiency of continuous stirred tank (CSTR) type reactor in treating wastewater having a low COD concentration (Ling et al., 2015). Zhu et al. have studied the effect of flow pattern on pollutant removal and concluded that plug flow reactor is 1.58 and 1.21 times more efficient than static and stirred tank reactors respectively in COD removal (Zhu et al., 2015). A similar observation has been reported during electrochemical oxidation of textile industry wastewater in batch and continuous flow recirculation system (Basha et al., 2012). Concentric tubular reactors are the most common continuous plug flow reactors tested (Körbahti and Tanyolaç, 2009; Körbahti, 2007). However, the distribution of current density is not uniform in a concentric tubular electrochemical reactor, and a flat velocity profile is exhibited (Ling et al., 2015; Wang et al., 2015). Among the various reactors, parallel plate reactors are one of the simplest and easy-to-scale-up reactors for industrial application (Cano et al., 2016; Chen, 2004; de Vidales et al., 2016; Oduoza and Wragg, 2002). Baffled reactors perform

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better than those without baffles (Oduoza and Wragg, 2002; Wragg and Leontaritis, 1997). The high mass transfer rate of the serpentine flow baffled reactors makes it an attractive choice for the reactor configuration (Oduoza and Wragg, 2002).

The present study focuses on testing the applicability of a novel parallel plate continuous serpentine flow reactors having a plug flow regime for the electrochemical oxidation of textile wastewater. The efficiency of the reactor was evaluated for the treatment of synthetic and real textile wastewater. Energy consumption and mass transfer coefficient were calculated to estimate the performance of the reactor. Economic analysis and a comparison of the performance of the reactor with respect to energy consumption and cost of treatment) with that of a batch stirred tank reactor were carried out.

2. Materials and methods

2.1. Chemicals and wastewater sample

Methyl orange, malachite green, starch, sodium carbonate, sodium bicarbonate, sodium chloride, sodium hydroxide and sulphuric acid used for the preparation of synthetic textile wastewater were purchased from Merck and were of the highest purity available. The composition of the synthetic textile wastewater is provided in Table 1.

Textile wastewater was collected from an industry situated in West Bengal, India. The collection point was the influent drain to the effluent treatment plant of the industry and was characterized (Table 2). Total solids and total suspended solids were measured gravimetrically. Ion chromatography was used to measure chloride, sulphate, and nitrate. Carbonate and bicarbonate were measured titrimetrically (Clesceri et al., 2005). Electrochemical oxidation was carried out in a continuous flow baffled reactor.

2.2. Experimental setup

The details of the reactor are reported elsewhere (Pillai and Gupta, 2015a). The details of the instruments used in the experimental setup are reported elsewhere (Pillai and Gupta, 2015a; Pillai et al., 2015). A schematic representation of the experimental setup is given in Fig. 1. Lead dioxide electrodeposited on mild steel (MS/PbO_2) (Pillai and Gupta, 2015b) was used as anode and graphite plate was used as the cathode (immersed area 104 cm^2). The lead electrode was confirmed to be stable and devoid of leaching of lead under extreme operational conditions (Pillai and Gupta, 2015b).

2.3. Experimental procedure

The operational parameters (viz. current density (1.15 mA cm^{-2} – 2.69 mA cm^{-2}) and flow rate (250 mL h^{-1} – 750 mL h^{-1})) were optimized one variable at a time (uniparameter optimization) for the degradation of synthetic textile wastewater at ambient temperature (28 ± 2 °C) and natural pH of the solution (8.5–9). The composition of the synthetic wastewater was varied, and its effect on the degradation at a flow rate of 500 mL h^{-1} and a current density of 1.15 mA cm^{-2} was also noted.

Electrochemical oxidation of real textile wastewater was carried out and the operational parameters including current density (0.38 mA cm^{-2} – 1.54 mA cm^{-2}), supporting electrolyte concentration (0.5 g L^{-1} – 2 g L^{-1}) and flow rate (250 mL h^{-1} – 750 mL h^{-1}) were optimized at ambient temperature (28 ± 2 °C) and natural pH of the solution (9.5). Samples were collected at half an hour interval and pH, colour intensity, and COD were measured. All the analysis were carried out as per standard methods for the examination of water and wastewater (Clesceri et al., 2005).

Table 1
Composition of synthetic textile wastewater.

Chemical	Concentration (mg L^{-1})
Methyl orange	100
Malachite green	100
NaCl	1500
Na_2CO_3	500
$NaHCO_3$	500
NaOH	500
H_2SO_4	800
Starch	500

Table 2
Characterization of textile industry wastewater.

Parameter	Unit	Before degradation	After degradation
Colour		Grey-Green	Colourless
COD	mg L^{-1}	368	BDL
BOD	mg L^{-1}	160	BDL
pH		9.5	7.03
Turbidity	NTU	69.3	16.8
TS	mg L^{-1}	1860	437
TSS	mg L^{-1}	28	18
TDS	mg L^{-1}	1620	354
Conductivity	mS cm^{-1}	4.28	4.04
Chloride	mg L^{-1}	113	944
Sulphate	mg L^{-1}	4982	402
Nitrate	mg L^{-1}	BDL	42
Carbonate	mg L^{-1}	140	73
Bicarbonate	mg L^{-1}	880	430

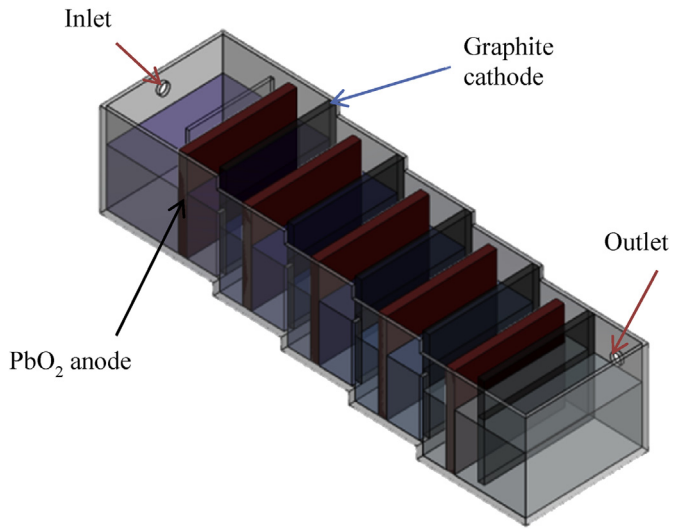

Fig. 1. Schematic representation of the parallel plate continuous serpentine flow reactor (Volume – 1.5 L; Depth of flow – 5 cm; Area of electrodes – 104 cm^{-2}).

2.4. Analytical

Energy consumption in an electrochemical system is the estimate of the electrical power consumed for the degradation of 1 kg COD. It is calculated as shown in Eq. (1).

$$EC = \frac{UIt}{\Delta COD \times V_R} \quad (1)$$

Where U is the voltage (V), I is the current (A), t is the retention time in h, ΔCOD is the COD reduction in g L^{-1} and V_R is the volume of the

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