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ScienceDirect
Ultrasonics Sonochemistry 15 (2008) 49–54
Ultrasonics SONOCHEMISTRY
www.elsevier.com/locate/ultsonch

Treatment of industrial wastewater effluents using hydrodynamic cavitation and the advanced Fenton process

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Received 14 September 2006; received in revised form 10 January 2007; accepted 13 January 2007
Available online 3 February 2007

Abstract

For the first time, hydrodynamic cavitation induced by a liquid whistle reactor (LWR) has been used in conjunction with the advanced Fenton process (AFP) for the treatment of real industrial wastewater. Semi-batch experiments in the LWR were designed to investigate the performance of the process for two different industrial wastewater samples. The effect of various operating parameters such as pressure, H_2O_2 concentration and the initial concentration of industrial wastewater samples on the extent of mineralization as measured by total organic carbon (TOC) content have been studied with the aim of maximizing the extent of degradation. It has been observed that higher pressures, sequential addition of hydrogen peroxide at higher loadings and lower concentration of the effluent are more favourable for a rapid TOC mineralization. In general, the novel combination of hydrodynamic cavitation with AFP results in about 60–80% removal of TOC under optimized conditions depending on the type of industrial effluent samples. The combination described herein is most useful for treatment of bio-refractory materials where the diminution in toxicity can be achieved up to a certain level and then conventional biological oxidation can be employed for final treatment. The present work is the first to report the use of a hydrodynamic cavitation technique for real industrial wastewater treatment.

Keywords: Hydrodynamic cavitation; Advanced Fenton process; Industrial wastewater treatment; Optimization

1. Introduction

The spectacular effects of cavitation in terms of production of highly reactive free radicals, conditions of high temperature/pressure and generation of intense turbulence and liquid circulation currents can be effectively harnessed for wastewater treatment applications [1,2]. Indeed, ultrasonically induced cavitation has been used with great success for degradation of various pollutants though, almost exclusively, on a laboratory scale of operation [3–9]. However scale up of ultrasonically induced cavitation is a problem due to ineffective distribution of the cavitational activity on a large scale and inefficient operation of the transducers at levels of higher power dissipation/higher frequency [10,11]. An alternative form of cavitation generated in a liquid circulatory flow, termed hydrodynamic cavitation, has been reported to be energy efficient as compared to acoustic cavitation and scale up of hydrodynamic cavitation reactors is also relatively easy as compared to acoustic cavitation reactors [12,13]. In our earlier work [12], it has been shown that a hydrodynamic cavitation set-up results in an energy efficiency of about 60–65% depending on the operating conditions whereas conventional sonochemical reactors such as an ultrasonic horn or ultrasonic bath results in an energy efficiency of merely 10–20%. Use of hydrodynamic cavitation reactors in real industrial wastewater treatment applications has been rarely investigated possibly due to lower intensity of cavitation generated in the reactors. There have been only a few reports of treatment of synthetic wastewater samples and these have only contained one major pollutant. Sivakumar and Pandit [14] have studied the applicability of hydrodynamic cavitation

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1350-4177/$ - see front matter
doi:10.1016/j.ultsonch.2007.01.003

reactors for degradation of Rhodamine B samples (a pink coloured dye solution) and reported that hydrodynamic cavitation was indeed much more energy efficient compared to acoustic cavitation. The hydrodynamic cavitation unit using multiple hole orifice plates has been reported to give cavitational yields (extent of degradation per unit energy supplied), which are two times higher than the best acoustic cavitation device (dual frequency flow cell with an capacity of 1.5 L). Kalumuck and Chahine [15] have also reported similar results for the degradation of *p*-nitrophenol using multiple zones of hydrodynamic cavitation in a re-circulatory pipe flow. It has been reported that the cavitating jet system gives about 20 times the rate of degradation compared to the ultrasonic horn (irradiating frequency of 15.7 kHz and power density of 0.36 W/mL) and the oxidation efficiency (mg degraded per unit energy supplied) is almost 25 times more for the cavitating jets.

A unique approach can be to use a combination of hydrodynamic cavitation with other advanced oxidation processes so as to harness the spectacular effects in an energy efficient manner [16]. In the present work, a combination of hydrodynamic cavitation with the advanced Fenton process (AFP) has been applied to real industrial wastewater samples, procured directly from chemical processing industries. It should be noted here that the majority of studies in the past have used synthetically made effluents (by dissolving a pure pollutant in water) for evaluating the efficacy of cavitation as a tool for wastewater treatment. The extent of degradation achieved under these conditions may not be reproduced with actual industrial wastewaters as these often contain variable amounts of other compounds and solvents that act as radical scavengers. Thus, the importance of the present work, which uses real wastewater samples, is clearly emphasized.

AFP utilizes zero valent iron pieces as the catalyst, which considerably reduces the cost of the treatment, and generates hydroxyl radicals when used in conjunction with hydrogen peroxide under acidic pH conditions [17–22]. It is hypothesized that initially iron metal is corroded in the presence of H_2O_2 under acidic conditions oxidizing Fe^0 to Fe^{2+}, which then further reacts with H_2O_2 in a Fenton-like process to generate hydroxyl radicals and Fe^{3+}. The Fe° then reduces the Fe^{3+} back to Fe^{2+} and the cycle continues. The detailed mechanistic aspects including the chemical reactions occurring in this cycle have been described in our earlier work [17,18]. Hydroxyl radicals thus generated by the Fenton process using zero-valent iron pieces are powerful oxidising species that react with the toxic pollutants present in the wastewater thereby breaking the large, toxic organics into relatively innocuous smaller molecules. As the mechanism of oxidation in both the techniques (hydrodynamic cavitation and the advanced Fenton process) is the broadly the same involving hydroxyl radicals, an amalgamation of the two is expected to give synergistic results.

The current study is unique as there have been no earlier reports on the use of a combination of hydrodynamic cavitation and AFP for treatment of real industrial wastewater samples.

2. Experimental methods

2.1. Characteristics of the industrial wastewaters

The experimental studies were performed to evaluate the efficacy of the combination technique for degradation of two different industrial wastewater effluents (sources not revealed due to confidentiality issues). Industrial effluent 1 consisted of a complex mixture containing substituted phenolic compounds with a pH of 1.7, initial chemical oxygen demand (COD) of 42,000 mg/L and original total organic carbon (TOC) content of 14,000 mg/L. Industrial effluent 2 was a pink dyestuffs solution, which had a pH of 10.4, COD of 17,000 mg/L and TOC of 6000 mg/L. COD indicates the concentration of all organic compounds which can be fully oxidized using strong oxidizing agents whereas TOC usually indicates the amount of all the organics present in the system.

2.2. Experimental set-up

Hydrodynamic cavitation was generated using a liquid whistle reactor (LWR), which is coupled to a positive displacement pump and is employed in a comprehensive system containing the motor, base, variable frequency drives, pressure and flow measuring devices. The system consists of a feed vessel tank with a 5 L capacity, a plunger pump (Giant Industries, Model P220A, USA) with a power consumption of 3.6 kW and having a speed of 1750 rpm and a mixing chamber comprising of an orifice (orifice area, $7.74 \times 10^{-7}\ m^2$) and a blade (length, 0.0268 m; width, 0.0222 m; thickness, 0.0015 m). The pump has a maximum discharge pressure of up to 2000 psi (13,788 kPa). The distance between the orifice and the blade is adjustable and the backpressure valve connected at the end of the mixing chamber influences the pressure. The presence of the orifice generates a high velocity liquid jet, which is projected over the edge of the blade, kept adjacent to the orifice (Fig. 1). The process liquid sheds vortices perpendicular to the original flow in between the orifice and blade, creating a steady oscillation, which imposes pressure fluctuations on the cavitating bubbles generated due to the sudden reduction in the pressure at the orifice. The use of the blade also creates a situation similar to the use of two orifices in the system, which results in an increase in the extent of cavitation. A schematic representation of the intensified hydrodynamic cavitation generated by the LWR in conjunction with the AFP is shown in Fig. 1.

2.3. Experimental methodology

All experiments were carried out with 4 L of wastewater (diluted accordingly with fresh water), supplied by two