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Industrial wastewater treatment using hydrodynamic cavitation and heterogeneous advanced Fenton processing

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ABSTRACT

A combination of hydrodynamic cavitation and heterogeneous advanced Fenton process (AFP) based on the use of zero valent iron as the catalyst has been investigated for the treatment of real industrial wastewater. The effect of various operating parameters such as inlet pressure, temperature, and the presence of copper windings 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 increased pressures, higher operating temperature and the absence of copper windings are more favourable for a rapid TOC mineralization. A new approach of latent remediation has also been investigated where hydrodynamic cavitation is only used as a pre-treatment with an aim of reducing the overall cost of pollutant degradation. It has been observed that approach of latent remediation works quite well with about 50–60% removal of TOC using only minimal initial treatment by hydrodynamic cavitation.

1. Introduction

Due to increasing awareness about the environment and more stringent environmental regulations, treatment of industrial wastewater has always been a key aspect of research. Much work has been done in developing and testing newer techniques and their combinations for wastewater treatment either individually or as a supplementary role to the conventional biological and chemical methods [1,2]. Cavitation is one such recent technique which has been found to be substantially beneficial in wastewater treatment [3]. Cavitation can be described as formation, growth and subsequent collapse of cavities releasing large magnitudes of energy locally, creating conditions similar to hot spots, and also generating strong oxidizing conditions by way of production of hydroxyl radicals and also hydrogen peroxide. The reactors, based on the use of ultrasonic irradiation for generation of cavities, have been categorized as sonochemical reactors whereas when cavities are generated using hydrodynamic means (interchange of flow energy and pressure energy) they are termed, hydrodynamic cavitation reactors. Considerable work has indeed focussed on the application of sonochemical reactors for wastewater treatment [3–10] for a variety of pollutants. However, very few studies have reported the use of the much more energy efficient hydrodynamic cavitation reactors for wastewater treatment [11,12]. It should also be noted here that, though cavitational (particularly sonochemical) reactors have been reported to be highly successful on laboratory scale operation, these still have been not able to find application on an industrial scale mostly due to comparatively higher costs of treatment and problems associated with efficient operation at levels of power dissipation required for treatment [13]. The efficacy of cavitational reactors can be significantly enhanced by combining cavitation with other oxidation processes or by using catalysts and/or additives. With this intensification, cavitation can be a suitable technology for degradation of wastewater streams or at the minimum it can be used for lowering the toxicity levels of the effluent stream so that conventional biological oxidation can be readily applicable [14]. It may not be practical, especially considering the economics of the process, to use cavitational reactors for complete mineralization but it is strongly recommended as a pre-treatment strategy especially for high COD effluent streams as considered in the present work. In our earlier recent work, a novel combination of hydrodynamic cavitation reactors and the advanced Fenton process was applied to the destruction of real industrial wastewater procured from a commercial organization in UK at an operating capacity of 4 L [15]. We have also reported on hydrodynamic cavitation, generated using a liquid whistle reactor, and acoustic cavitation in conjunction with the advanced Fenton process (AFP) utilizing zero valent iron metal in the form of scrap iron pieces as the heterogeneous catalyst [16–18] with an aim of reduction in the overall cost of the treatment. It was observed that hydrodynamic cavitation was found to play a supplementary role in enhancing the efficacy of AFP and the combination of the two

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resulted in higher overall extents of degradation. The current work is in continuation of the earlier work and utilizes a newly constructed hydrocavitator for generation of hydrodynamic cavitation with a maximum operating capacity of 25 L. The paper presents an advancement over the earlier work in terms of experimental data on a larger scale of operation with an aim of enhancing the confidence among prospective users for commercial applications, use of additional oxidants with a possibly of reducing the treatment times and an investigation of the effect of operating temperatures which affects the efficacy of advanced Fenton oxidation. Also, as cavitational reactors have been found to be cost intensive [13], an novel approach of latent remediation has been investigated wherein the treatment time with hydrodynamic cavitation reactors has been kept at a minimum in order to achieve lower overall costs of treatment.

2. Materials and methods

2.1. Experimental setup

Hydrodynamic cavitation was generated using an in-house constructed unit termed a Hydrocavitator which has a feed vessel tank with maximum capacity of 25 L and operates in re-circulation mode. Effluent from the feed tank is pumped using a triplex plunger pump (SPECK NP25) with a maximum discharge pressure of 4500 psi (31,020 kPa) and passes through an orifice unit (orifice area about 7.0×10^{-2} m^2) followed by a catalyst bed and finally back to the feed tank. An external ice bath is used to control the temperature in the feed vessel tank, which is necessary as cavitation results in production of heat thereby increasing the temperature of the effluent stream. A schematic representation of the reactor assembly is shown in Fig. 1.

2.2. Characteristics of industrial wastewater

The experimental studies were performed to evaluate the efficacy of the combination technique for degradation of industrial wastewater effluent obtained from a local site (details not given due to confidentiality issues). The current investigation is very important in the context of the application to wastewater treatment as the majority of the reported literature deals with simulated effluents and the results may, or may not, be reproduced for real industrial applications due to the presence of trace components such as radical scavengers.

The effluent stream used in the present work consisted of a complex mixture containing substituted phenolic compounds with an initial pH of 1.7, initial COD of 42,000 mg/L and TOC of 14,000 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.

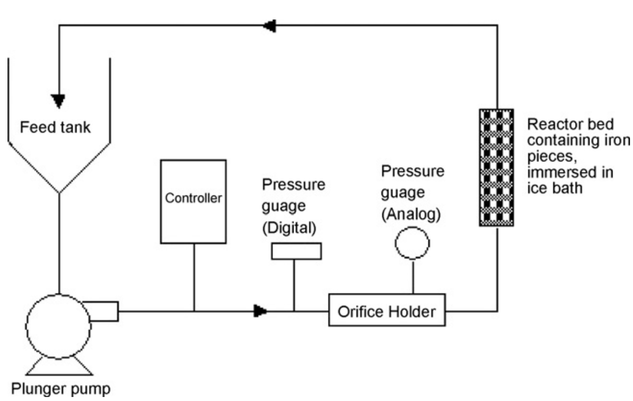

Fig. 1. Schematic representation of the experimental setup.

2.3. Experimental methodology

All experiments were carried with 8 L of wastewater (25 times dilution with fresh water) with a reaction time of 150 min with zero valent iron pieces (150 g as 100 pieces with dimensions of 1 cm × 2 cm × 0.10 cm) and H_2O_2 (usually 1900 mg/L unless specified otherwise). The concentration of H_2O_2 has been found to be the optimum concentration in our earlier investigations on a smaller scale of operation with an operating capacity of 4 L [15] as compared to an operating capacity of 8 L in the present work. Passage of the hydrogen peroxide through the iron bed results in generation of hydroxyl radicals and this has been described as advanced Fenton process [15–18]. Solutions of sulphuric acid (2 M) and sodium hydroxide (2 M) were used for the adjustment of pH. An operating pH of 2.5 was selected for all the experimental runs based on the fact that maximum efficacy of the cavitational reactors as well as Fenton chemistry is observed over an operating pH range of 2–3 [1]. The temperature was maintained constant using an external cooling ice bath.

At defined time intervals, samples were taken and analysed for TOC content present in the solution, as optimal mineralization of the effluent stream was the main objective of the investigation. The extent of mineralization was determined by direct injection of the filtered samples into the heated persulphate-type (100 °C) TOC analyser (Model 700, OI Analytical).

In the current work, all the experiments were carried out in duplicate to estimate the repeatability of the obtained data which were analysed by statistics tools provided by Excel, MS Office 2003. The graphs were plotted using mean values obtained from the data and the standard deviation of the replicate values is shown as error bars in the values depicted on *Y*-axis. All the experimental errors were found to be within ±2% of the mean reported value.

3. Results and discussion

The experimental results obtained by varying the parameters of inlet pressure into the system, operating temperature of the reactor and the role of additional copper windings on the AFP will be discussed.

3.1. Effect of initial pressure

Preliminary control experiments without the use of the advanced Fenton process indicated that hydrodynamic cavitation alone results in very little degradation and that using an iron catalyst in the presence of hydrogen peroxide is a definite requirement. The effect of different initial pressures of the hydrocavitator in conjunction with the AFP was investigated over the range of 500–1500 psi (3446.7–10,340 kPa) and the results are shown in Fig. 2, where it is clear that higher inlet pressures are effective in the rapid mineralization of the wastewater. Maximum TOC removal ratio (about 60% removal) was obtained at 1500 psi (10,340 kPa) whereas the extent of TOC removal is 52% and 50% at 1000 psi (6893.3 kPa) and 500 psi (3446.7 kPa) respectively under otherwise identical experimental conditions. The trends in the variation of TOC removal with inlet pressures are in close agreement with the reported literature [19–21]. The increase in the extent of degradation with increasing pressure can be attributed to the enhanced cavitational activity at higher pressures. Bubble dynamics studies [22] have indicated that the cavitational intensity generated at the collapse of the cavity increases with higher inlet pressure of the system. The increase in the cavitational collapse intensity generates