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A review on Application of Cavitational reactors for degradation of dye waste water from textile industries

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Abstract

Various dyes are released through textile industries into water bodies which are harmful to human beings and aquatic life. Recent pollution control norms forcing textile industries to treat their waste effluent to an increasingly high standard. Currently, dyes are removed by various physio-chemical & biological operations. These methods are very costly and do not eliminate dye completely also they convert them from primary pollutant to secondary pollutant by creating concentrated sludge which is difficult to dispose off. Therefore alternative technologies to remove these dyes without creating concentrated sludge. New technologies such as Cavitation & Advanced Oxidation systems are effective in removing dyes from large volumes of effluents and are low in cost. This review paper mainly focus on two methods of cavitation i.e. hydrodynamic and ultrasonic which are effective for dye degradation on large scale. The work highlights the basics of these individual processes including the optimum operating parameters and the reactor design aspects with a complete overview of the various applications to wastewater treatment in the recent years.

Keywords: Textile waste water, dye, Cavitation, Hydrodynamic cavitation, Ultrasonic cavitation

Introduction

Textile industries require large volume of water and variety of chemicals for textile processing which results in disposing these unused chemicals and polluting water bodies [1]. In india there are around 1000 small and large dye manufacturing units, who produce around 1,30,000 tonnes of dyestuff. Maharashtra and Gujarat account for 90% of dyestuff production in India due to the availability of raw materials and dominance of textile industry in these regions. The textiles industries alone uses 80 percent of dyes produced which is consumed mainly in polyester and cotton having very high demand globally [2].

Dyes obstruct light penetration in water bodies also decrease dissolved oxygen thus have negative impact on aquatic life. They also hinder photosynthesis in plant. Many dyes are difficult to decolorize due to their complex structure and synthetic origin. Currently, dyes are removed by various physio-chemical & biological operations. These methods are very costly and unable to remove dye completely creating resultant sludge which is difficult to dispose off. Therefore alternative technologies needed to remove these dyes without creating resultant sludge. New technologies such as Advanced Oxidation processes are effective in removing dyes from large volumes of effluents and are low in cost. Advanced oxidation process (AOP) mainly involves generation of highly reactive free radicals which further oxidizes complex organic compounds such as dyes. These processes include cavitation (acoustic and hydrodynamic cavitation) [3-5], chemical oxidation (use of ozone and hydrogen peroxide)[3,6], Fenton chemistry (reaction between Fe ions and hydrogen peroxide)[7-10], photocatalytic oxidation (using UV light/sunlight in the presence of heterogeneous catalyst)[11-14]. Most of these AOP techniques have been examined successfully on the laboratory scale but they are difficult to scale up on an industrial scale. Among these techniques cavitational reactors are novel and are the simplest to design and operate.

The two main mechanisms for the destruction of organic compounds using cavitation are (1) the thermal decomposition/ pyrolysis of the volatile organic molecule entrapped inside the cavity and (2) the reaction of free radicals with the organic compounds.[15-18].

Cavitation

Cavitation can be in general defined as the formation, subsequent growth and collapse of the cavities occurring in an extremely small interval of time (milliseconds) releasing large magnitudes of energy over a very small location resulting in very high temperatures (of the order of 1000 to 5000 K) and pressures (100 to 5000 bar) at millions of location in the reactor simultaneously with overall ambient condition [19]. Under such extreme conditions free radicals (OH and H radicals) are generated by dissociation of water molecules in cavitation bubbles. These radicals then diffuse into the bulk liquid medium and oxidize organic pollutants.

Types of cavitation based on mode of generation are as follows:

1. Acoustic cavitation: It is produced by sound waves, usually ultrasound (16 kHz-100 MHz) creates pressure variation in liquid medium which further produces cavities.

2. Hydrodynamic Cavitation: It is produced by pressure variation which is obtained by creating restriction to liquid flow using different geometry of the system mainly venture or orifice
3. Optic cavitation: It is produced by rupturing liquid medium by high intensity light photons.
4. Particle cavitation: It is produced by the beam of the elementary particles, e.g. a neutron or photon beam rupturing a liquid, as in the case of a bubble chamber.

Out of these four types of cavitation, only acoustic and hydrodynamic cavitation have been of academic and industrial interest due to the ease of the generation of the required intensities of cavitational conditions. Two parameters are important from design point of view in cavitation reactors, maximum size of cavity before collapse & life of cavity. The maximum size reached by cavity determines magnitude of pressure pulse on the collapse & life of cavity determines active volume of reactor. Thus designer should maximize both these quantities by adjusting different parameters including methodology used for generation of cavities.

Cavitation mechanism

There are two major effect of cavitation. Firstly cavity formed contains vapour from aqueous medium, when this cavity collaps, due to high temperature & pressure vapours generate highly reactive free radicals. These free radicals then react with organic compounds either inside collapsing bubbles or into bulk solution after migration. Secondly due to cavity collapse generating high vacuum forces liquid to fill the voids create shear force which break chemical bonds of dissolved organic compounds. Thus any increase in solvent vapour pressure decreases cavity collapse temperature & pressure. Thus for reaction where free radicals is primary cause of activation, low operating temperature is recommended with low boiling solvent. Whereas for a reaction requiring high temperature, high boiling solvent is recommended.

Sonochemical reactors

Ultrasonic horns is simple & most commonly used reactor designs amongst the sonochemical reactors. (Figure 1)

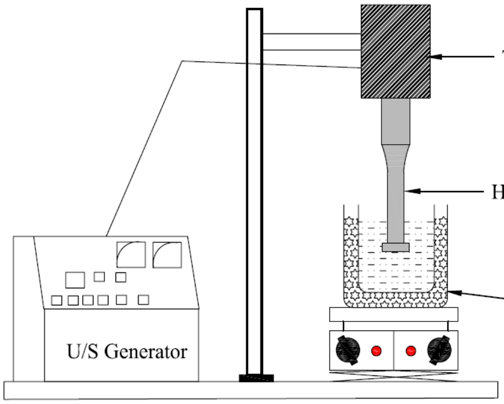

Figure 1: Ultrasonic Horn experimental set-up

In this type of reactor horn is immerged inside the solution and generate very high pressure (few thousand atmosphere) near horn. Pressure intensity decreases and get vanish beyond 2 to 5 cm away from horn depending on power input and operating frequency. [20]. Therefore acoustic energy cannot effectively transmit in large volume reactor. Ultrasonic horn suffers from erosion at the delivery tip surface which can block cavitation also large trasducer displacement create stress material of construction resulting in failure of material. Therefore application of ultrasonic horn limited for laboratory scale investigations.

Many researchers investigated use sonochemical reactors for the wastewater applications of which only few are maintained in terms of target chemical studied, type of the equipment and operating conditions.

Xi Kui Wang et al studied sonochemical degradation of methyl violet with a 20 KHz Model JCS-204 Ultrasonic Reactor with 100 ml of aqueous solution. Temperature was maintained in the range of 20-40oC. Degradation of methyl violet was found to be first order at 20±1°C with initial concentrations 5.0 mgL-1. With increase in concentration degradation rate decreased. Degradation rate decreased beyond 40oC. Degradation rate decreases from acidic to basic medium and lowest degradation was observed at pH < 10 [21]. Ritu Singla et al. investigated sonodemical degradation of Martius yello at ultrasound frequency of 355 kHz. Reactor used with 200 ml of solution and reaction temperature of 20±5oC. Degradation of dye observed due to hydroxyl radical attack involving primarily oxidative steps, & cleavage of C-N bond of chromophoric ring to yield carboxylic acid.[22]. Slimane Merouani et. al. studied degradation of Rhodamine B by 300 kHz ultrasound irradiation. It was found that degradation rate increases upto 300 mgL-1 & remain constact at higher concentration. Degradation rate increases duby increasing ultrasonic power which is maily due to increase in active cavitation bubbles. Optimum degradation was obtained in neutral range of 5-8 pH wheras it decreases in both acidic & basic medium. Degradation rate was also found to increase by 1.7 fold by increasing temperature from 25 to 55oC. [23]. Zeynep Eren, Nilsun H. Ince investigate the sonochemical degradability of two azo dyes C.I. Direct Yellow 9 (DY9) and C.I. Reactive Red 141 (RR141) at low frequency of 20 kHz and high frequency of 577, 861 and 1145 kHz at temperature of 20±0.5 ◦C. It was observed that high frequency ultrasound is more effective than low frequency ultrasound for decomposing these highly soluble azo dyes.[24]. C. Berberidou et al. investigated degradation of malachite green (MG) in water by means of ultrasound irradiation at a fixed frequency of 80 kHz and a variable electric power output up to 150 W. The reaction temperature was kept constant at 25±2oC. Degradation reaction is psedo first order & degradation rate increases with decreasing initial concentration upto 2.5 mgL-1 and increasing ultrasound power upto 135 W [25].

Hydrodynamic cavitation reactors

Typical hydrodynamic cavitation setup used most commonly consist of closed circuit loop containing holding tank with cooling jacket, reciprocating or centrifugal pump and cavitating devices venture or orifice plate as shown in figure 2.

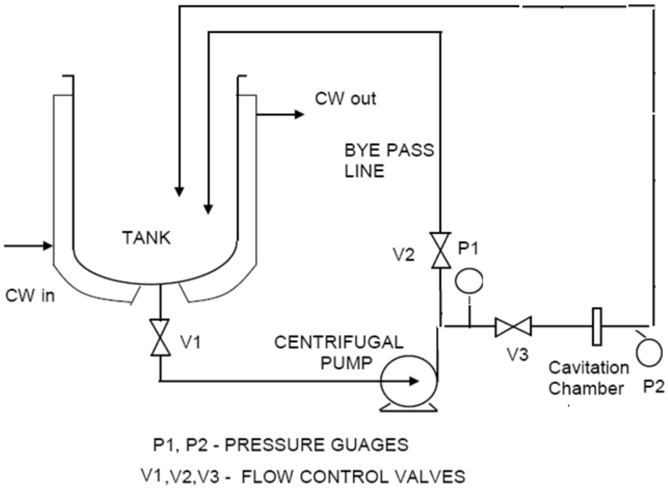

Figure 2: Orifice plate hydrodynamic cavitation setup

Hydrodynamic cavitation can simply be generated by providing restriction to liquid flow by orifce plate or venuri [26]. When the liquid passes through the constriction, the kinetic energy of liquid increases and local pressure decreases. If local pressure falls below the vapor pressure of liquid medium cavities will be generated. Downstream as the liquid boundary layer expands, the pressure recovers and this results in the collapse of the cavities. But during the passage substantial amount of energy is lost in the form of permanent pressure drop. A dimensionless cavitation number (Cv) generally gives relation between flow condition and cavitation intensity. Cavitation number calculated as:

$$C_v = \frac{P_2 - P_1}{(1/2)\rho_l v_0^2}$$

where P2 is the recovered pressure downstream of the constriction, Pv is the vapor pressure of liquid, vo is average velocity of liquid at the orifice and ρl is the density of liquid. The cavitation number at which the inception of cavitation occurs is known as cavitation inception number Cvi. Ideally, the cavitation inception occurs at Cvi=l and there are significant cavitational effects at Cv value of less than 1[27]. Parag R. Gogate and Aniruddha B. Pandit shows that magnitude of pressure pulse generated decreases with Cv>1 decreasing cavitational intensity and no collapse of cavities at Cv =2). However Harrison and Pandit observed cavitation to occur at higher cavitation number due to impurities or some dissolved gases in liquid medium. [28] Yan and Thorpe (1990) shows cavitation number increases with increase in size and diameter of constriction. Therefore to achieve maximum efficiency, flow conditions & geometry of cavitating device should be selected to achieve cavitation number below 1 but should not be very low causing supercavitation which will lock vapurs and no cavitational collaps.[29]

Many researchers investigated use hydrodynamic reactors for the degradation of dye from waste water of which only few are listed below in terms of target chemical studied, geometry of cavitating device and operating conditions.

Madhu G M et. al studied degradation of malachite green and methyl violet solution. Experimental setup uses holding tank of 40 L capacity with centrifugal pump of 1.5 kW and 2900 RPM. Orifice plates with different numbers and different diameter holes were used. It was found that degradation rate increases with increasing pressure upto 5 kg/cm2 & increasing pH upto 11 at which 100% degradation of malachite green and 95.22% degradation of violet dye was observed after 40 min & 60 minutes respectively. It was also observed that degradation rate increases with decrease in orifice diameter & cavitation number [30]. Parag R. Gogate, Ghanshyam S. Bhosale studied degradation of orange acid-II (OA-II) and brilliant green (BG) with hydrodynamic cavitation. Experimental setup consist of closed loop circuit with holding tank of 4L capacity with orifice plate of 25 mm diameter with 2 mm hole size as cavitating device and a reciprocating pump (power rating 1.1 kW. It was observed that decolorisation increases by increasing pressure upto 5 kg/cm2 & then decreases by increasing pressure upto 7 kg/cm2 [31]. Kashyap P. Mishra, Parag R. Gogate studied degradation of Rhodamine B, a waste dye effluent using hydrodynamic cavitation. Setup consist of closed loop circuit including holding tank of 4 L capacity, reciprocating pump of power rating 1.1kW, venture and orifice plate as cavitating devices. It was observed that venturi gives more degradation than one hole orifice plate. Degradation rate was increased by increasing inlet pressure upto 4.84 atm and above that it decreases. Degradation rate also increases by increasing temperature upto 40oC. Acidic conditions are more favourable for degradation of dye & maximum degradation was obtained at pH 2.5. [32]. V.K. Saharan et al. studied degradation of Orange-G dye by hydrodynamic cavitation. The experimental setup includes a holding tank of 15 L volume, a positive displacement pump of power rating 1.1 kW and three different cavitating devices namely circular venture, slit venture and circular orifice plate. It was observed that degradation of Orange G dye follows first order kinetics & degradation rate increases with increase in initial concentration of dye. It was also observed that decolorisation rate increases with decrease in pH and maximum degradation of 75.72% was observed at pH 2.0. Much lower decolorisation was observed in basic medium. It was also observed that slit venture is more effective than circular venuri & orifice plate for higher cavitational yield & higher efficiency of degradation.[33]

Conclusions

Cavitational reactors appear to be very effective for treatment of textile waste water also lead to considerable economic saving. For specific applications with better product distribution at ambient conditions sonochemical reactors are better than conventional reactor systems. It can be said that hydrodynamic cavitation reactor better suit for large scale industrial applications compare to sonochemical reactors due to operational cost and also scale up of these reactors is comparatively easy. Optimisation of various parameters for both type of ractors is necessary to get maximum benefits. Overall cavitational reactors technology is well established on lab scale applications which need to be applied at industrial scale by combination of science and enginnering.

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