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Review on Wastewater Treatment by Hydrodynamic Cavitation

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Abstract: *The use of acoustic cavitation for water and wastewater treatment (cleaning) is a well known procedure. Until now, the use of hydrodynamic cavitation as a lone technique or in combination with other techniques such as ultrasound has only recently been suggested and employed. In this paper a general overview of techniques that employ hydrodynamic cavitation for treatment of water and wastewater is presented.*
Keywords: *Applications, advantages, hydrodynamic cavitations, venturi, wastewater treatment,*

I. 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]. Cavitation consists of the generation, growth and subsequent collapse of gas filled cavities (bubbles) due to pressure pulses inside a liquid bulk [13]. Bubbles generate and grow when the external pressure over the liquid decreases to an inception value, usually around the vapour pressure of the liquid. After reaching a maximum size, and as pressure recovery takes place, the non-equilibrium state gives raise to bubble collapse, which under certain conditions, can be considered implosive. When bubbles implode, the compression effects upon its internal gases might cause temperature increases up to 103-104 K [13,14] and pressure peaks of 102-103 bar [15]. Due to the extreme P-T conditions inside the bubbles, water dissociates into H· and OH· radicals [16]. The hydroxyl radical is a very strong oxidant (ε0=2.79 V) and most substances are readily oxidized in its presence. The processes that generate them, i.e. combinations of UV+(TiO2/H2O2/O3/Fe2+), are commonly known as Advanced Oxidation Processes (AOPs). Cavitation can be considered an AOP in which the bubbles behave as micro reactors as they implode. Due to the oxidation potential of OH· radicals, AOPs are generally considered as very effective techniques in water treatment. Nevertheless operation costs are usually high due to the presence of UV light and/or chemical reactants. Cavitation offers two important advantages over conventional AOPs due to the fact that neither reactants nor UV light are used: first, it requires significantly lower operation costs than the rest of the AOPs; and second, the by-products are limited to those expected from the oxidation of the contaminants, avoiding the presence of other dangerous oxidants such as chlorine.

II. Hydrodynamic Cavitayion

Hydrodynamic cavitation (HC) can simply be generated by the passage of the liquid through a constriction such as an orifice plate.When the liquid passes through the orifice, the kinetic energy/velocity of the liquid increases at the expense of the pressure. If the throttling is sufficient to cause the pressure around the point of vena contracta to fall below the threshold pressure for cavitation (usually vapor pressure of the medium at the operating temperature), millions of cavities are generated. Subsequently as the liquid jet expands, the pressure recovers and this results in the collapse of the cavities. During the passage of the liquid through the constriction, boundary layer separation occurs and a substantial amount of energy is lost in the form of a permanent pressure drop. Very high intensity turbulence occurs on the downstream side of the constriction; its intensity depends on the magnitude of the pressure drop, which, in turn, depends on the geometry of the constriction and the flow conditions of the liquid. The intensity of turbulence has a profound effect on the cavitation intensity [17]. Thus, by controlling the geometric and operating conditions of the reactor, one can produce the required intensity of the cavitation so as to bring about the desired change with maximum efficiency. Also the collapse temperatures and pressures generated during the cavitation phenomena are a strong function of the operating and geometric parameters [18]. Figure 1 shows a typical setup to generate cavities hydrodynamically. The pressure-velocity relationship of the flowing fluid as explained by Bernoulli's equation can be exploited to achieve this effect. The flowing liquid, when it passes through a mechanical constriction, say an orifice or a partially throttled valve, venture or an orifice (part a in Figure 1), its velocity increases accompanied by increase in kinetic energy and corresponding decrease in the local pressure (part b in Figure 1). If the throttling is sufficient to reduce the absolute local pressure below the vapor pressure (at the operating temperature), spontaneous vaporization of the medium in the form of micro-bubbles (nucleation) occurs. With continued lowering of the pressure, the cavity continues to grow by further vaporization or desorption of gases (if some gas is dissolved in the medium) reaching its maximum size at the lowest pressure. Subsequent increasing (pressure recovery) of the pressure compresses this from fully grown cavity and is made to collapse in adiabatic phase, thus generating the kind of extreme condition of pressure and temperature.

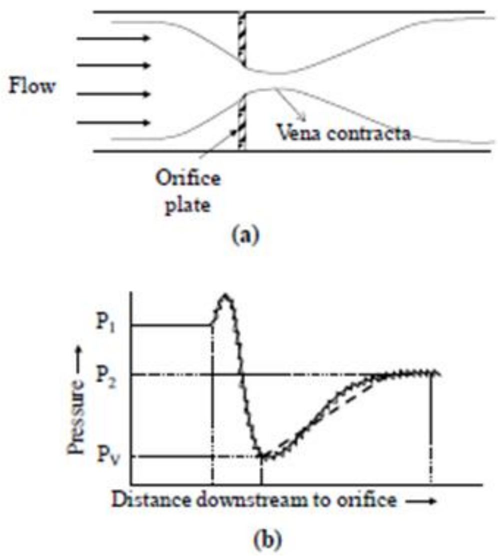

Figure 1: Fluid flow & Pressure variation in hydrodynamic cavitation set-up

A dimensionless number known as cavitation number is used to relate the flow conditions with the cavitation intensity. Cavitation number is given by the following equation no. 1:

$$C_V = \left(\frac{p_2 - p_v}{\frac{1}{2}\rho v_o^2} \right) \qquad \text{-----(1)}$$

Where, p2 is the fully recovered downstream pressure, pv is the vapor pressure f the liquid, vo is the velocity at the throat of the cavitating constriction. The cavitation number at which the inception of cavitation occurs is known as the cavitation inception number Cvi. Ideally speaking, the cavitation inception occurs at Cvi equal to 1 and there are significant cavitational effects at Cv values of less than 1. In the earlier work [18], it has been shown that the cavities oscillate under the influence of fluctuating pressure field and the magnitudes of pressure pulses generated are much less, insignificant to bring about a desired chemical change for the case where Cv values are greater than 1. However, cavitation has been found to occur at a higher cavitation number also, possibly due to the presence of dissolved gases or some impurities in the liquid medium [19]. It was observed that for a given size orifice, the cavitation inception number remains constant within an experimental error for a specified liquid. The cavitation inception number does not change with the liquid velocity and is a constant for a given orifice size and is found to be increasing with an increasing size and dimension of the orifice [17]. The effect of geometry of cavitating device (orifice plates) on the inception of cavitation are given by Yan and Thorpe [20]. In the hydrodynamic cavitation, the cavitational yield (for e.g. amount of pollutant reduced per unit energy dissipated) depends on the intensity of cavity collapse which in turn depends on the several parameters such as number of cavitational events present, the maximum size of the cavity reached before its collapse and the surrounding pressure field. In hydrodynamic cavitation all these parameters depends on the geometry of cavitational device and the operating pressure. The important parameters which decide the efficiency and the overall cavitational yield are:

- Inlet pressure and the cavitation number
- Physicochemical properties of liquid and initial radius of the nuclei;
- Size and shape of the throat and divergent section (in the case of venturi)
- Percentage free area offered for the flow

The effect of the various design and operating parameters mentioned above has been studied extensively in terms of the collapse pressures on the basis of the numerical simulations using bubble dynamics equations [21, 22, 17, 18, 23, 24] and also on the basis of experiments done in different reactors [25,26, 27, 28,29].A study have carried out optimization of hydrodynamic cavitation using decomposition of potassium iodide as a model reaction. In this, it was studied the effect of various parameters (inlet pressure, flow geometry of orifice plates) on the iodine liberation rate. They have concluded that in hydrodynamic cavitation, altering flow geometry or increasing turbulence frequency (fT) and the fraction of the flow area occupied by the shear layer can enhance the cavitational yield. The optimum frequency of turbulence can be achieved by manipulating the flow conditions and geometry of the cavitation device. for the plates having the same flow area, it is advisable to use a plate with a smaller hole size opening, thereby increasing the number of holes in order to achieve a larger area of the shear layer. Because, for smaller hole sizes, the value of fT increases, leading to a more efficient collapse. On the contrary, for larger hole sizes the frequency of turbulence (fT) is likely to be much lower than the natural oscillation frequency of the generated cavity, resulting in a lower collapse intensity. Also, if there is a choice on the magnitude of the flow area, lower percentage area should be chosen, as with a decrease in flow area, the intensity of cavitation increases [27]. Similar observations [28] have also been made in which carried out degradation of rhodamine-B using multiple hole orifice plates. The results of the numerical simulation in hydrodynamic cavitation carried [21] were also consistent with the experimental observations made [27]. Experiments have carried out optimization of the important geometrical parameters of a cavitating venture and found that the ratio of the perimeter of the venturi to the cross sectional area of its constriction quantifies the possible location of the inception of the cavity. The ratio of the throat length to its height (in the case of a slit venturi) controls the maximum size of the cavity and the angle of the divergence section controls the rate of collapse of a cavity. Based on the numerical study, it was concluded that a slit venturi ($\alpha = 2.7$) with the slit length equal to its height (1:1) and a half angle of divergence section of 5.5 degrees is an optimum geometry for best cavitational activity [25]. The effect of different operating parameters (inlet pressure and cavitation number) on the cavitation yield using KI degradation were studied and found out that the rate of iodine liberation increases with an increase in inlet pressure, reaches a maximum and then decreases, similarly the rate increases with a decrease in cavitation number, reaches a maximum and then drops [27].The similar observation using the bubble dynamic simulation for the hydrodynamic cavitation devices [18]. All of the above studies depicted that, in hydrodynamic cavitation, the cavitational yield (efficiency of hydrodynamic cavitation in bringing about the desired changes physical and chemical changes) depends on the geometrical parameters as well as on operating parameters (operating pressure and cavitation number). Till date most of the studies were carried out using the single and multiple hole orifice plate having circular hole only, and hence there is a huge scope in the field of the design of different hydrodynamically cavitating devices including different types of venture having different size and shape such as circular and noncircular shape (rectangular, square, elliptical, etc.), and orifice plates having throat of different shapes.

III. Advantages of Hydrodynamic Cavitation

Ultrasonic cavitation has been extensively studied during the last decade. Its capability to oxidize organic substances is comparable to that of other AOPs, but due to its difficulties to perform at industrial scale, the technique has been studied from a scientific point of view rather than an engineering one. Hydrodynamic cavitation, has also proven efficient to oxidize organic substances such as volatile organic compounds, trichloroethene and BTEX [30]. Although experimental procedures are less flexible, and optimization harder to achieve the technique offers some important advantages over ultrasonic cavitation. Hydrodynamic loops, which essentially consist of a pump, a tank, a Venturi tube and pipes, are cheaper than ultrasonic equipment for a given scale (especially for industrial scale).Operation costs, based on energy efficiency, are also lower for hydrodynamic cavitation [31, 32]. And most important, the hydrodynamic devices work at medium and large-scale, in opposition to ultrasonic cavitation, which have only shown its efficiency at lab-scale. Regarding final results in water treatment, very little work has been done attempting direct comparisons between ultrasonic cavitation and hydrodynamic cavitation. Time scales for bubble growth and collapse are around 103-104 fold smaller for ultrasonic cavitation. This fact along with direct observations suggest that both bubble size and cloud density are much higher in hydrodynamic cavitation, which means that the effective reaction volume will also be higher. On the other hand individual bubble behaviour is not clear. As bubbles grow bigger some of them break up into micro bubbles. Those which remain stable collapse with a non-spherical shape, giving raise to effects which theory can hardly predict.

IV. Applications of Hydrodynamic Cavitation

Ability of cavitation to deliver energy, in concentrated and desired form and on length and time scales similar to that of transformation, makes it an attractive tool to be utilized to bring about the transformations in an energy efficient manner. As a result of this, cavitation is applied for several applications which utilize the primary and secondary effects to bring about the transformations. Primary effects are the ones which are direct result of volumetric oscillations or the collapse of cavity, while secondary effects are those which occur as the result of primary effects. Primary effects include extremely high pressure temperature (~ 10000 K), high pressure (~ 2000 atm) and high velocity liquid microjets (~ 100 – 300 m/s) [25]. It is because of these primary effects that cavitation is capable to bring about intensification of processes. Some secondary effects which are the key benefits of cavitation include free radical generation, enhancement of mass transfer rates, and increase in interfacial area. A few applications of cavitation are listed below.

- Waste water treatment
- Water disinfection
- Biological cell disruptions
- Hydrolysis of fatty oils
- Pulp and paper digestion
- Preparation of nano particle
- Mixing and uniform dispersion
- Chemical synthesis

As explained earlier, the collapse of cavities releases large magnitude of energy with transient temperature of 10000 K and pressure of about 2000 atm. Under these extreme conditions (high temperature and pressure) water and other dissolved gases can dissociate into free radicals (for e.g. water molecules dissociate into H• and OH• radicals). These hydroxyl radicals thus generated reacts with the pollutant molecules trapped inside the cavities and also these OH• radicals diffuses into the bulk liquid medium where they react with the pollutant molecules and oxidize them. The other mechanism which causes destruction of organic pollutant is the thermal pyrolysis of pollutant molecules trapped inside the cavities or present near the cavity surface during cavity collapse. There are not many reports indicating the applications of the hydrodynamic cavitation reactors in wastewater treatment schemes until now. The destruction of *p*-nitrophenol in recirculating flow loops using a variety of cavitating jet configurations and operating conditions and have shown that, hydrodynamic cavitation can effectively degrade *p*-nitrophenol. Submerged cavitating liquid jets were found to generate a two orders of magnitude increase in energy efficiency compared to the ultrasonic method. The ultrasonic destruction was studied in an ultrasonic horn [33]. The hydrodynamic cavitation having orifice plate with multiple holes can be used for the destruction of the rhodamine B complex in an efficient way as compared to acoustic cavitation. Acoustic cavitation was studied using an ultrasonic horn (Operating frequency: 22.7 kHz; power input: 240 W; and capacity: 50 ml) an ultrasonic bath (Operating frequency: 22 kHz; power input: 120 W; and capacity: 0.75 l) as well as a dual frequency flow cell. They have found that the cavitational yield (grams of rhodamine B degraded per unit energy supplied) for the hydrodynamic cavitation set-up was approximately two times higher as compared to the best in the sonochemical reactors (dual frequency flow cell, operating frequency: combination of 25 and 40 kHz; power input: 240 W; and capacity: 1.5 l) Moreover, the hydrodynamic cavitation set-up is able to degrade approximately 50 l of effluent under a single operation as compared to a few milliliters in the case of the ultrasonic horn and bath and 1.5 l for the ultrasonic flowcell (31). The degradation of potassium iodide using hydrodynamic cavitation.They have concluded that the intensity and number of cavitation events can be effectively controlled by using different plates differing in number and diameter of holes. They have found that the flow geometry of the orifice plates considerably affects the rate of the iodine liberation. They have recommended that for the plates having the same flow area, it is advisable to use a plate with a smaller hole size, thereby increasing the number of holes (higher α, the ratio of total perimeter of holes to the total area of the opening) to get the maximum cavitational effects [30]. The mineralization of 2,4-dichlorophenoxyacetic acid by acoustic and hydrodynamic cavitation in conjunction with the advanced Fenton process. They have compared the efficacies of acoustic and hydrodynamic cavitation in enhancing the degradation process. It was observed that in 20 min of treatment time(beyond this time, the increase in the TOC removal is only marginal), the combination of acoustic cavitation and the advanced Fenton process gives around

60% TOC removal, whereas 70% TOC removal is observed with hydrodynamic cavitation combined with the advanced Fenton process. They have concluded that the use of zero-valent iron and hydrogen peroxide in conjunction with acoustic or hydrodynamic cavitation is a very effective means of destroying high concentrations of 2,4-dichlorophenoxyacetic acid. A combination of advanced Fenton process and cavitation has been observed to intensify the degradation process by way of turbulence and generation of additional free radicals. The results achieved using the hydrodynamic cavitation are particularly good in that this unit operates in a continuous mode and hence large volumes of contaminated water might be treated very cost-effectively particularly with low levels of polluted water, at equivalent energy dissipation levels [34]. 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. They have observed that increased pressures, higher operating temperature and the absence of copper windings are more favorable for a rapid TOC mineralization. They have concluded that higher inlet pressures result in greater cavitational activity contributing to the enhanced hydroxyl radical generation and hence increased TOC mineralization of the effluent. Around 60% mineralization can be achieved at 1500 psi inlet pressure as compared to 50% at 500 psi inlet pressure. They have observed that the addition of copper has a negative impact on the mineralization of organic pollutants present in wastewater. About 60% of TOC was removed in the presence of iron pieces alone and only 40% of TOC was removed with copper windings on iron pieces after 150 min of treatment. This was explained on the basis of relative rates of hydroxyl radical generation due to the presence of iron and copper. It is well accepted that the rate of hydroxyl radical generation and hence the extent of TOC mineralization is much higher in the presence of iron as compared to copper metal [35].The degradation of alachlor aqueous solution by using hydrodynamic cavitation. They have found that alachlor in aqueous solution can be effectively decomposed with swirling jet-induced cavitation. The effects of operating parameters such as fluid pressure, solution temperature, initial concentration of alachlor and medium pH on the degradation rates of alachlor were also discussed. The results showed that the degradation rates of alachlor increased with increasing pressure and decreased with increasing initial concentration. An optimum temperature of 40ºC existed for the degradation rate of alachlor and the degradation rate was also found to be slightly depend on medium pH [36]. The degradation of reactive brilliant red K- 2BP (K-2BP) in aqueous solution using swirling jet-induced cavitation combined with H2O2. It was observed a synergetic effect between hydrodynamic cavitation and H2O2. The degradation of K-2BP by hydrodynamic cavitation combined with H2O2 follows pseudo first-order kinetics. A variety of experimental conditions were investigated for the degradation of K-2BP by swirling jet-induced cavitation combined with H2O2. It was found that lower pH and higher temperature of medium, higher pressure of fluid, more addition of H2O2 and lower dye initial concentration are favorable for the degradation of K-2BP using hydrodynamic cavitation [37]. Recently, a investigation on degradation of an aqueous solution of dichlorvos using hydrodynamic cavitation reactor gives the the effect of various additives such as hydrogen peroxide, carbon tetrachloride, and Fenton's reagent on the degradation rate with an aim of intensifying the degradation rate of dichlorvos using HC. They have observed that use of hydrogen peroxide and carbon tetrachloride resulted in the enhancement of the extent of degradation at optimized conditions but significant enhancement was obtained with the combined use of hydrodynamic cavitation and Fenton's chemistry. The maximum extent of degradation as obtained by using a combination of hydrodynamic cavitation and Fenton's chemistry was 91.5% in 1 h of treatment time [38]. The above works depict that hydrodynamic cavitation has great scope in the area of wastewater treatment because of its effectiveness in reducing the organic pollutant and real industrial wastewater to a desirable level, cost effective method as compared to other advanced oxidation technique and easy to scale up on an industrial scale. Though hydrodynamic cavitation offers immense potential and also higher energy efficiency and cavitational yields, use of these reactors is perhaps lacking on larger scales. More work is indeed required both on theoretical front as well as on the experimental front for better understanding of the phenomena and subsequent design methodology.

V. Conclusion

It has been concluded that hydrodynamic cavitation can be effectively utilized for the degradation of biorefractory pollutants. This study shows that hydrodynamic cavitation has a potential of application on an industrial scale, while its successful implementation on an industrial scale depends on several parameters such as geometrical, operating (operating pressure and cavitation number) and physicochemical properties (density, viscosity and pH of the solution) of wastewater to be treated. The following conclusion can be drawn from this study. It has been found that hydrodynamic cavitation is capable of oxidizing organic pollutants and further the efficiency can be enhanced by regulating operating parameters (operating pressure and cavitation number) and physico-chemical properties of the fluid to be treated. The studied carried out in chapter 2 and 3 indicates that inlet pressure and cavitation number are the two important parameters which affects the degradation rate of dyes.

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