Hydrodynamic Cavitation as a low-cost AOP for wastewater treatment: preliminary results and a new design approach

Y. Benito[1], S. Arrojo[1], G. Hauke[2] & P. Vidal[2]
[1]*Effluent Treatment Program, Ciemat, Spain*
[2] *Centro Politécnico Superior. Universidad de Zaragoza, Spain*

Abstract

The phenomenon of Cavitation gives rise to a number of interesting physical-chemical effects which can be employed to isolate and oxidize contaminants in water. The micro bubbles generated by pressure pulses inside a liquid act as small reactors, reaching extreme P-T conditions during short periods of time and generating highly oxidant radicals such as OH·. This chemical behaviour is analogous to that of Advanced Oxidation Processes (AOPs). While cavitation generated by ultrasound has proven efficient, reliable and easy to optimise, hydrodynamic cavitation should be studied as a valuable alternative. Although it implies a number of disadvantages in terms of experimental procedures and flexibility, its performance at industrial scales is better. This paper reports the potential of hydrodynamic cavitation as an AOP for wastewater treatment, showing its suitability and efficiency against a wide variety of contaminants (biodegradable, recalcitrant, organic and inorganic) and concentrations, with very low operation costs, simple equipments and no reactants required. The objective is to summon the theoretical and experimental evidence of this potential, constructing the computational tools and the experimental devices which will be used to overcome the uncertainties and optimise the technique.
Keywords: wastewater treatment, hydrodynamic cavitation, acoustic cavitation, AOP.

1 Introduction

Cavitation consists of the generation, growth and subsequent collapse of gas filled cavities (bubbles) due to pressure pulses inside a liquid bulk [1]. 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 10^3-10^4 K [1,2] and pressure peaks of 10^2-10^3 bar [4]. Due to the extreme P-T conditions inside the bubbles, water dissociates into H· and OH· radicals [5]. The hydroxyl radical is a very strong oxidant (ε_0=2.79 V) and most substances are readily oxidized in its presence. The processes that generate them, i.e. combinations of UV+(TiO_2/H_2O_2/O_3/Fe^{2+}), 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.

The new European water directive for contaminants in water regulates additional non-biodegradable substances, setting lower maximum concentrations allowed in wastewater. While the governments gradually transpose this directive the industry is being forced to search for technical alternatives to fulfil the new law. The application of AOPs such as UV and ozone for water treatment is increasing steadily in the industry. Cavitation could have the same potential applications for wastewater treatment avoiding some of the most problematic characteristic of conventional AOPs.

2 Hydrodynamic vs. ultrasonic cavitation

Cavitation is classified by the means of generating the pressure pulses, and can be divided into ultrasonic cavitation and hydrodynamic cavitation. The first one consists of pressure waves generated in an ultrasonic bath or through an ultrasonic horn inside a liquid bulk, whilst the latter is based on the pressure variations due to acceleration/deceleration of a liquid flow.

Thanks to the advent of inexpensive and reliable laboratory generators of high-intensity ultrasound on the 1980s, the generation of chemical mechanisms induced by ultrasonic cavitation gave rise to a new field known as sonochemistry. Ultrasound cavitation has proven to efficiently remove a wide variety of contaminants in water [6,7]. Ultrasonic equipments (horns and baths) are probably the best way to effectively study the phenomenon of cavitation. Most commercial equipments are prepared to work at lab scale. The parameters of the pressure pulse, such as amplitude or frequency, are easy to control and reproduce. Moreover, the whole process takes place inside a static liquid with no change in the ambient conditions, and therefore observations and measurements are easy to perform. Due to these advantages, ultrasonic cavitation has been the main object of study for most groups interested on cavitation. Nevertheless, important problems have been found up-scaling the equipment. Large bulk liquids cushion ultrasound waves, and the liquid only cavitates in the proximity of the ultrasonic horns, what causes significant decreases in the efficiency of the process.

It is generally agreed that hydrodynamic cavitation implies a number of practical problems in both operation control and direct measurements. Cavitation Loops are usually designed for medium and large scale operations (tanks from 10 to 1000 liters). In contrast with ultrasonic cavitation, the process takes place in a high velocity flow inside a closed pipe. This is the source of additional complexity and limitations regarding the control over the pressure pulse. It is unclear whether turbulence, boundary layer separation and other hydrodynamic factors are positive or negative in terms of final effects of the technique, but they have certainly prevented many researchers from studying the potential applications of hydrodynamic cavitation. This paper intends to prove that the aforementioned difficulties should not be a reason to leave this new field unexplored.

2.1 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 [8]. Although experimental procedures are less flexible, and optimisation 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 [9]. 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 10^3-10^4 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.

3 Experimental

3.1 Hydrodynamic cavitation

The plant designed to produce hydrodynamic cavitation, the Cavitation Loop, consists of a tank (containing the contaminated liquid), a discharge pipe with a pump and a convergent/divergent section (Venturi tube or orifice plate) known as cavitation chamber after which the liquid flows back to the tank. Cavitation is forced through high-speed loop circulation. The liquid first accelerates in the convergent section, as a result pressure decreases and therefore bubbles generate and grow. In a second stage the liquid enters a diverging section and decelerates, giving raise to pressure recovery and bubbles implosion. The liquid is circulated and cavitated during a period of time that varies from case to case (generally between 15 and 90 minutes).

The experiments were carried out in a medium scale cavitation loop (50 liters tank). The liquid was circulated at a flow-rate of 5 m3/h, reaching a maximum velocity in the gorge of 30 m/s. The temperature was kept around 30ºC. To avoid degasification air was bubbled through the liquid inside the tank.

3.1.1 Reagents

Dodecane 99% Aldrich.
Salicylic acid 99% Aldrich.
2,5-Dihydroxibenzoic acid (2,5-DHB) 98% Aldrich.
Ammonia 30% (as NH_3) Aldrich.

3.1.2 Analytical techniques

Dodecane was determined with a Shimadzu GC-17A with a FID detector. Ammonia was measured with steam distillation/acidimetric NH3 analysis and the COD with the closed reflux titrimetric method. The OH· traps consisted of a 3 mM salicylic acid solution. The reaction product, 2.5 dihydroxybenzoic acid, was measured with a Kontron High Performance Liquid Chromatography (HPLC) system model equipped with a Waters model fluorescence detector.

3.2 Computational simulations

The most critical parameter in hydrodynamic cavitation is the pressure pulse. The potential of the technique is strongly dependent on the degree of control over this parameter. The computational fluid-dynamic simulation tool Fluent ® will be used as the first step to understand, predict and optimise the behaviour of different designs for cavitation chambers.

Taking a step forward, the development of programs to simulate cavitating bubbles will be the ultimate tool to evaluate the theoretical capability of hydrodynamic cavitation as an AOP.

4 Results and discussions

4.1 Experiments with cavitation loop

The first experiment was made with a 100 ppm dodecane solution to prove the capacity of the technique to oxidize organic aliphatic substances. After 60 minutes of operation 99% of dodecane was oxidized.

The technique was also applied to a solution of ammonia with a concentration of 3000 ppm. The conversion after 90 minutes was 45%.

Next, in order to evaluate the capacity of the cavitation loop to treat complex systems of biodegradable substances with high concentration, a real sample of pig manure (excrements and urine with a CDO around 75000 mg O2/L) was cavitated during 90 minutes, obtaining a reduction of the CDO up to 60%.

And last, radical traps of salicylic acid were used for indirect measurements of OH· radicals in order to evaluate the effectiveness of the cavitation loop as an AOP, obtaining a radical generation of 4×10^{16} OH· radicals/(liter/min).

No additional reactant was used during the aforementioned experiments.

These experimental procedures were a first stage, which intended to give an approximate idea of the cavitation loop potential and limitations.

4.2 Cavitation chamber design with Fluent

The following discussion is the summary of extended fluid-dynamic computational studies with Fluent ®. These theoretical results have been used to design the new cavitation loop.

Venturi tubes: Venturi tubes are the most common design to generate a pressure pulse. Divergent section can be modified essentially by changing the angle of divergence. At a first glance one might think that bigger angles lead to faster decelerations and therefore faster pressure recovery, but the situation is rather the opposite. Abrupt divergences produce boundary layer detachment and therefore eddies and recirculations. As a result of this effect the pressure losses increase, and the pressure recovery decreases proportionally. Moreover, negative velocities significantly delays the deceleration of the water jet along the axis. Therefore, the attempt to obtain abrupt pressure recovery in the divergence by increasing the divergence angle results both into lower pressure recovery and lower pressure rate of change.

On the other hand if the divergence angle is too small, the residence time of fluid particles in the Venturi will increase. The pressure recovery will reach a maximum, but the pressure rate of change will decrease. Fig. 1 shows the dynamic behaviour for a given Reynolds number of a divergent section with different divergence angles. Since these are not final results optimum behaviour requires experimental studies, or further simulations using these data to simulate cavitating bubbles facing the predicted pressure pulses.

Orifice plates: The simplest device to induce cavitation are orifice plates, which basically consist on a metal plate with one or various orifices. Orifice plates can also be considered as a Venturi tube with a convergent/divergent angle of 90 degrees. While being the simplest and cheapest possible configuration for a cavitation chamber, orifice plates are also energy inefficient. The disadvantages of abrupt divergences appear in this case at their maximum rate, and can also be seen in fig.1. Nevertheless some authors have reported that turbulences generated with the orifice plates might give raise to positive effects on cavitation [10].

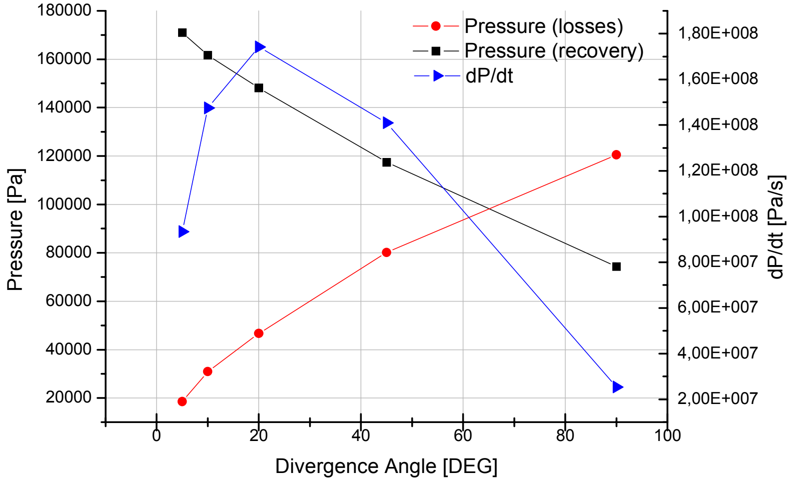

Figure 1: Pressure losses, pressure recovery and pressure rate of change (dP/dt) for a divergent section with different angles (Re (gorge) = 2 x 10^5)

Impact plates: Impact plates are obstacles which block the water jet after the gorge. By doing so the jet finds a high pressure point. As a result pressure recovery and pressure change rate increase significantly along the water jet. Additional pressure losses are also significant, but these happen downstream of the recovery pressure stage, and therefore should not interfere with the cavitation process. Impact plates might be a very useful configuration to attain high power cavitation as long as the distance between the plate and the gorge is high enough to avoid mayor pressure increase inside the gorge, which would prevent bubbles to grow or even generate.

4.3 Bubble simulation

The computational simulation of the cavitating system is achieved by solving some 14 differential equations: modified Rayleigh-Plesset equation, energy conservation, state equation, position of the bubble inside the cavitation chamber and 10 conservation of species equations. The numerical integration of these equations permits solving: the pressure and temperature inside the bubble, its radius, the velocity of the bubble walls, the position of the bubble in the cavitation chamber and the mass fraction of the 10 species considered inside the bubble. The numerical integration is implemented using the DVODE subroutine, a variable-coefficient ordinary differential equation solver.

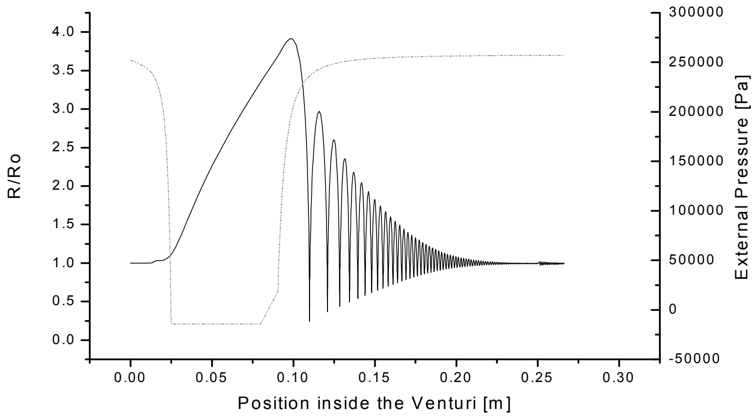

Figure 2: R/Ro of an isolated bubble (radius over initial radius) (continuous line), confronting a pressure pulse(discontinuous line).

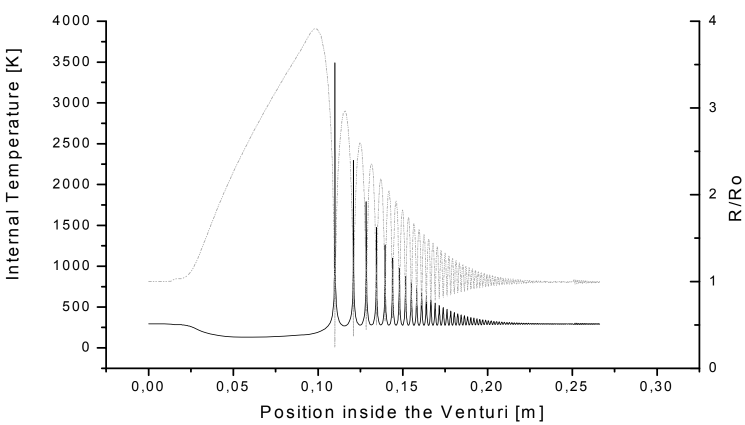

Figure 3: Evolution of internal temperature of the bubble (continuous line), produced by bubble oscillations (R/Ro) (discontinuous line).

Fig. 2 and 3 represent an isolated bubble inside a cavitation chamber. The hydrodynamic pressure pulse produce bubble growth, collapse, and various rebounds until it reaches equilibrium. The collapse and subsequent rebounds produce instantaneous temperature peaks which are responsible for the chemical effects that convert bubbles into micro reactors.

4.4 Theoretical behaviour of hydrodynamic cavitation as an AOP

The combination of the two computational tools will be used as an evaluation of the potential of hydrodynamic cavitation as an AOP. Introducing pressure pulses calculated with Fluent ® as an input data of the bubble simulation program we can estimate the thermal effects of cavitation.

Fig. 4 shows the maximum temperature achieved inside a cavitating bubble facing different pressure pulses. The pressure pulses are defined by the pressure recovery and the pressure rate of change, and they correspond to the calculated data shown in fig. 1.

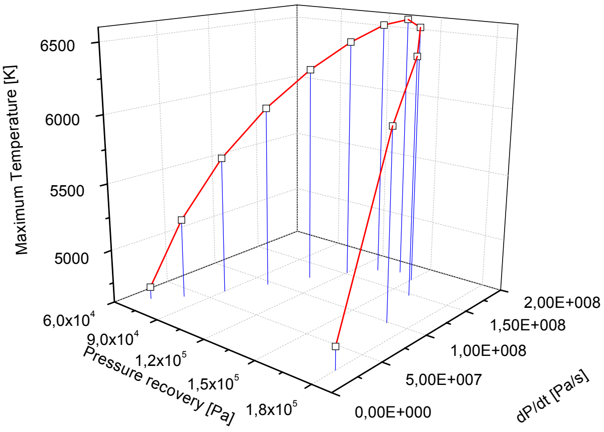

Figure 4: Maximum internal temperature of cavitating bubbles facing different pressure pulses (calculated in Fluent simulations corresponding to different divergent sections of a Venturi tube).

The temperatures reached with hydrodynamic cavitation are similar to those reached inside ultrasonic cavitation bubbles. As it has been said, bubble cloud density, and therefore effective reaction volume, is expected to be higher for hydrodynamic cavitation. Therefore there is enough evidence to consider this technology a potentially efficient AOP for water treatment, with some additional difficulties, but with a number of significant advantages over the competing techniques.

5 Conclusions: new design for the cavitation loop

Theory proves that hydrodynamic cavitation is suitable and effective as an AOP, nevertheless due to limitations in the experimental setups, researchers have failed

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to reach the expected results. The new design of the cavitation loop is a whole new concept based on the results obtained with the help of computational tools and previous results. The objective was to overcome the main difficulties related to the technique of hydrodynamic cavitation. The cavitation chamber has been constructed to visualize the phenomenon through two polymethacrylate windows. This allows not only direct observations, but also photography taking, film shooting and even direct measurements of the bubble clouds.

The configuration of the cavitation chamber is flexible and very easy to change, choosing from different types of Venturi tubes, orifice plates and impact plates.

The physic-chemical data of the liquid are obtained from the tank (temperature, pH, conductivity and oxygen concentration), and a by-pass is arranged to obtain continuous measurements from a spectrophotometer (with a flow-cell). The pressure profile is measured with eight pressure transducers located all along the cavitation chamber

The visibility, flexibility in the design and on-line measuring devices of the new cavitation loop will be a step forward in the understanding of the phenomenon of hydrodynamic cavitation. The extended experimental procedures and optimisation of the technique with the new cavitation loop will determine the real potential of this technique for its application as an AOP for wastewater treatment, confirming or refuting the promising results that have been obtained so far.

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