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A critical review of the current technologies in wastewater treatment plants by using hydrodynamic cavitation process: Basic principles

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Abstract

In the last years, hydrodynamic cavitation (HC) was increasingly used for a variety of applications in the field of wastewater treatment, ranging from biological applications (i.e. cells disruption) to chemical reactions such as oxidation of organic, bio-refractory and toxic pollutants in aqueous effluents. HC is induced in fluids by subjecting them to velocity variations due to the presence of constrictions in the flow. This process involves the formation, growth, implosion and subsequent collapse of micro-bubbles, occurring in extremely small intervals of time and releasing large magnitudes of energy over a very small location. In this paper, the vast literature on HC is critically reviewed, focusing on the basic principles behind it, in terms of process definition and analysis of governing mechanisms of both HC generation and pollutants degradation. The influence of various parameters on HC effectiveness was assessed, considering fluid properties, construction features of HC devices and technological aspects of processes. The synergetic effect of HC combined with chemicals or other techniques was discussed. An overview of the main devices used for HC generation and different existing methods to evaluate the cavitation effectiveness was provided. Knowledge buildup and optimization for such complex systems from mathematical modeling was highlighted.

Keywords

Hydrodynamic cavitation; Computational Fluid Dynamics; Modeling; Pollutant degradation; Wastewater treatment.

Highlights

1. Synergetic effect of HC combined to thermo-chemical treatments.
2. Definition of optimum operating conditions for the combined processes.
3. Investigation on HC intensity and pollutants degradation.
1. Introduction

In the past decades, HC process has been the subject of study by many researchers worldwide. This phenomenon has been widely studied in order to understand the reason of its negative effects on hydraulic machinery such as pumps, turbines, valves, etc. [1–6]. Many efforts have been made in order to better understand mechanisms of the HC process with the main aim of preventing its generation and trying to avoid severe physical damages such as erosions, vibrations and noises in hydraulic machinery [1,5]. With this purpose, many studies have been carried out in order to define methods and parameters to predict and, then, avoid cavitation inception [7].

On the contrary, in recent years to cope with a decrease in available water resources worldwide, an increasing demand of water by population in developing countries, and higher restrictive environmental legislations on water quality, HC has been increasingly applied as an innovative technique in the field of wastewaters treatment. Fig. 1 shows the robust increase in the number of peer-reviewed publications stored in the databases of Scopus on innovative wastewater treatments and, further, on the application of HC as novel technique in the field of wastewater treatment.

Due to its elevated oxidative capability, HC has been used for a variety of applications as a sole technique or in combination with other techniques, ranging from biological processes such as cell disruption to chemical treatments such as oxidation of organic pollutants in aqueous effluents, including bio-refractory and toxic chemicals [8,9].

Generally, the effectiveness of cavitation process in wastewater treatment has been widely proved by using acoustic cavitation (AC) [10,11], which has shown to overcome some limitations of the advanced oxidation processes (AOPs) that are commonly not capable of completely degrading complex compounds. In the last decade, restrictions due to high costs related to AC applications have been overcome by the development of HC technologies [12]. If compared to others conventional treatment techniques, HC is proving to be characterized by higher removal efficiencies, lower energy required by the system [13,14], and lower issues of secondary contaminations.

AC cavitation has been widely applied to treat wastewater. On the contrary, HC has been studied to a lesser, but published studies on its application have shown promising outcomes in different fields such as biological treatments in WWTPs (activated sludge [15–18], pre-treatment of biomasses before anaerobic digestion [19], denitrification [9] processes, and activated sludge reduction [14]), removal of carcinogen and toxic dyes [8], pharmaceuticals, toxic cyanobacteria, bacteria and viruses [20].
2. Brief background of cavitation process

Cavitation can be defined as the phenomena of generation (inception), growth, coalescence, fission, travelling and implosive collapse of cavitation bubbles or cavities (Fig. 3) within a liquid in less than a few microseconds. It results in very high local temperature (several thousands of K) and pressure (several thousands of atm) [21,22], inducing physical and chemical effects, in addition to the mechanical ones. Depending on the mode of its generation, cavitation can be classified in acoustic cavitation (AC), hydrodynamic cavitation (HC), optic cavitation (OC) and particle cavitation (PC). OC and PC can occur when a liquid is irradiated with light of high intensity or by means of a laser. In OC, photons are used to rupture the liquid, whereas in PC other types of elementary particles such as protons and neutrinos can accomplish a breakdown in the liquid [23]. In AC and HC, cavities are generated as result of local pressure drops due to pressure and velocity fluctuations, respectively. Although all four types of cavitation generate cavitation bubbles, it was found that only AC and HC are able to make the desired chemical changes in treated matters in the environmental field [24,25].

Following, the well-known thermodynamic concept of vapor pressure will be used to explain the physical meaning of the cavitation process based on local pressure drops. As shown in Fig. 2, in the phase diagram of water the curve from the triple point to the critical point separates the liquid and vapor domains. Crossing that curve is representative of a reversible transformation under static or equilibrium conditions. Phase transformations from the liquid phase to the vapor phase (evaporation) or, vice versa, from the vapor phase to the liquid phase (condensation) occur at a specific value of pressure known as the vapor pressure, $p_v$, for each temperature value. Cavitation is very similar to boiling, except that the main driving mechanism is not a temperature change but a pressure change. After cavitation bubbles grow in low-pressure regions into the liquid, they can be transported by convection into higher pressure regions where they can collapse [26].

When cavitation occurs, a specific multiphase of gases (vapour and air) and liquid into the fluid can be detected. If the pressure of mixture equals the saturated pressure, the vapour cavitation occurs. On the contrary, for pressures lower than the atmospheric one, it can be observed a release of air from the liquid. Because void creation and void filling with vapor and/or air are simultaneous, the instantaneous saturation of the void can be justifiably assumed [26].

It is widely accepted that cavitation inception is strongly subject to water quality, especially in relationship with nuclei concentration into the water. Occurrence of cavitation bubbles starts from weak points in the water, namely bubble nuclei, which break the bond between the water molecules. These nuclei are generally tiny gas bubbles or solid nuclei.

Despite some differences in the generation of cavitation bubbles by using AC and HC, the principles that govern the hydrodynamic and the acoustic bubbles growth are the same. In AC, when ultrasound wave propagates into the liquid, it generates compressions and rarefactions. The compression cycles exert a positive pressure on the liquid by pushing the molecules together, whereas the rarefaction cycle exerts a negative pressure by pulling the molecules from one another. Due to the low pressure, cavitation bubbles are
generated in the rarefaction regions. These bubbles grow in successive cycles and reaches to an unstable diameter collapsing violently [27]. In HC, due to the presence of a constriction into the fluid that usually implies a reduction in the flow cross section, low flow pressures are achieved, resulting in the generation of cavitation bubbles. At the downstream of the constriction, as the cross section expands, the flow pressure recovers and this results in growth of bubbles achieving an unstable diameter whereby the cavities collapse violently [28]. Bubbles that occur in a cavitating flow are often far from spherical. However, it is often argued that the spherical analysis exhibits satisfactory higher-level bubbles dynamic modeling. Moreover, it is often assumed that an isothermal bubble growth up to the maximum radius occurs, in which the bubble is mainly filled with vapor and/or air at equilibrium at the ambient temperature [29].

Many studies have been carried out to investigate on the dynamics of bubbles collapse [30], showing the presence of several peculiar phenomena that can take place in a very short period, while the overall environment remains at the ambient atmospheric conditions. After the growth phase, bubbles can collapse, generating new rebound bubbles of smaller size that can grow and collapse several times again. This phenomenon, known as rebound, is due to the presence of gas trapped into the bubbles during the collapse [31,32]. Rebound bubbles can also sometimes break into several bubbles (fission of bubbles). The shape of rebound bubbles depends on the symmetry or asymmetry of the dynamics of the collapse. A perfectly spherical collapse produces a spherical rebound bubble, while an asymmetry leads to the deformation of the bubble and to the generation of a micro-jet emerging from the rebound bubble [32]. A micro-jet can reach velocities in the order of 100 m/s [33], increasing the turbulence and the mass transport coefficient. Because of their high velocity, micro-jets can contribute to promote changes in water clusters, agglomerations of fibres and molecules. During the collapse phase, the high velocity of the bubble interface and the compressibility of the liquid lead to the generation of shock waves into the liquid. At this stage, very high temperatures of several thousand of K can occur [21], but these last for a very short time (in 1 sec the temperature drops to the temperature of the surrounding fluid). Such extreme conditions are sufficient to dissociate vapours trapped into the cavitation bubbles, resulting in the generation of free radicals, such as \( \bullet \text{H} \) and \( \bullet \text{OH} \), which are very strong and not specific oxidizing species [34,35]. At the very last stage of the collapse, pressure and temperature of the gas into cavitation bubbles can be so high that light is emitted. This phenomenon of light emission is known as luminescence [36].

Cavitation can be further classified considering the degree of its intensity, which depends on magnitude of pressure or temperature. According to this classification, cavitation can be either transient or stable [27]. In transient cavitation, radius of cavitation bubbles expands to at least twice its initial size. Then, cavitation bubbles can collapse to a minute size of its original one in a limited time frame, resulting in a no mass flow of permanent gas through the bubble-liquid interface [25] and causing a very violent implosion. This allows the release of a significant amount of energy in the form of an acoustic shock-wave and as visible light. At this stage, temperature of vapor within the cavitation bubbles and pressure can achieve several thousand of K and several hundred of atm, respectively. In stable cavitation, on the other hand, cavitation bubbles contain more gas and thus they have a less violent collapse compared to transient cavitation bubbles. The shock-
waves and micro-jets caused by stable cavitation bubbles implosions usually generate a lower pressure compared to the transient ones [37–39]. In HC, it has been experimentally proved that if the intensity of turbulence is quite low, the recovery pressure downstream to the constriction can be approximated by a linear expression with respect to the distance downstream of the constriction where stable cavitation occurs. When the intensity of turbulence increases and the recovery pressure is no more linear the behaviour of cavitation bubbles can be defined as transient [40].
3. HC generation and mechanisms

Due to the introduction in the flow of some constrictions such as orifice plates, Venturi systems or throttling valves, flow velocities and, hence, flow pressure can be modified, resulting in HC generation. According to the Bernoulli principle (Eq. 1), when the liquid passes through the constriction, the flow velocity (Fig. 4 a) and, then, the flow kinetic energy increase at the expenses of the flow pressure (Fig. 4 b):

\[
\frac{v^2}{2g} + \frac{p}{\rho g} + z = \text{constant}
\]

Eq. 1

where \( V \) is the velocity of the flow at a point on a streamline, \( g \) is the acceleration due to gravity, \( z \) is the elevation of the point above a reference plane, \( \rho \) is the pressure at the chosen point, and \( \rho \) is the density of the fluid at all points in the fluid.

When cavitation occurs, the total energy remains constant, but some of this energy is converted into turbulence and heat during the process; therefore, the downstream flow pressure will always be less than the upstream flow pressure. If the throttling of the constriction is sufficient, the flow pressure at the throat of the constriction can equal or fall below the vapor pressure of the liquid at the given temperature, and the vaporous cavities can be generated.

This condition can be formulated as reported in the following equation, Eq. 2:

\[ p_{\text{min}} = p_v \]

Eq. 2

where \( p_{\text{min}} \) is the minimum static flow pressure and \( p_v \) is the vapor pressure at a given temperature of the liquid. Depending on the geometry of the constriction, with further lowering of the pressure, the cavities can continue to grow, reaching their maximum size at the lowest flow pressure and subsequently when the cross section expands, resulting in a decrease in flow velocity, the flow pressure recovers and this can result in the implosion and the collapse of these earlier formed cavities [28,41], (Fig. 4 c).

3.1. HC flow regimes

In characterizing cavitating flows, the most used parameter has been the cavithalional number \( C_v \). It is a dimensionless number that can be expressed as reported in the following equation, Eq. 3:

\[ C_v = \left( \frac{p_r - p_r(T)}{\Delta p} \right) = \left( \frac{p_r - p_r(T)}{\frac{1}{2} \rho \cdot v^2} \right) \]

Eq. 3

where \( p_r \) is the recovery pressure [Pa] measured downstream the constriction where the flow becomes again undisturbed (a conventional reference point can be considered where cavitation inception is expected and flow pressure is easily measurable), \( p_v \) the vapor pressure of the liquid at the operating temperature \( T \) (i.e. 2.35 kPa at 25°C) [Pa], \( \Delta p \) the pressure difference that characterizes the system, and \( \rho \), \( V \) are the liquid density [kg m\(^{-3}\)] and the flow velocity [m s\(^{-1}\)] at the cavitating constriction, respectively.

The cavithalional number indicates the probability that cavitation occurs in a flow regime. As shown in Eq. 3, \( C_v \) is can be defined as the ratio between forces exerted by collapsing cavities respect those initiating their formation. Therefore, high values of \( C_v \) involve more collapsing forces and lower initiating forces, indicating
a lower cavitation activity. Cavitation may appear because of either a decrease in flow pressure at the reference point or an increase in the Δp-value.

Cavitation begins to occur for values of C_v below the cavitation inception number, C_v*. In most of studies, it was observed that the formation of cavities started at C_v equal to 1 [28]. However, cavitation can also start at C_v greater than 1 due to the presence of dissolved gases into the liquid and other solid particles which can act as pre-nuclei and thus they can accelerate the phenomena of cavities generation. For instance, typical values of C_v* are ranged from 1 to 2.5 for orifices flow in pipes [42].

Many reports indicate that with a decrease in C_v below 1, more cavities are formed, resulting in an increase in cavitation effects. It was also observed that a further decrease in C_v implies the achievement of a condition for which cavities can start coalescing with each other due to the large number and volumetric concentration of cavities, forming a vaporous cloud (choked cavitation / supercavitation), resulting in a decrease in cavitation intensity [43].

The threshold C_v* depends on all the usual factors considered in fluid mechanics such as flow geometry, viscosity, gravity, surface tension, turbulence levels, thermal parameters, wall roughness and gas content of liquid in terms of dissolved and free gases [33].

In HC, the comparison between the measured cavitation number and the threshold C_v* can lead to the identification of five different flow regimes [33]:

- **Non-cavitating flow**: when the pressure of the liquid is higher than the saturated vapor pressure, cavitation does not occur (C_v > C_v*). At this stage, known as non-cavitating flow phase, there is no evidence of cavitation bubbles into the fluid.

- **Cavitation inception or limited cavitation**: in this phase, the pressure of the liquid equals or falls below the vapor pressure of the liquid. Cavitation number is equal or slightly lower than the threshold value (C_v ≤ C_v*). Cavitation is just barely detectable, resulting in the appearance of scattered cavitation bubbles into the fluid. This phase is always characterized by strong noise of collapsing cavitation bubbles due to an instability of the generated cavities.

- **Developed cavitation**: even lower values of cavitation number (C_v << C_v*) allow the complete development of the cavitation bubbles.

- **Supercavitation**: this stage represents the final state of cavitation (C_v << C_v*). In this regime, the pressure in cavitation area is low and a big fixed cavity is formed. Compared with the other types of cavitation, the interface of a supercavitation cavity is stable. The cavity stays attached to the constriction and the cavity closure is downstream. The cavity acts as if it were an extension of the constriction. The length of the cavity does not vary significantly even though considerable oscillations can occur at its closure.

- **Desinent cavitation**: in this phase, cavitation bubbles completely disappear as the downstream flow pressure raises. Desinent cavitation is often used as a threshold between cavitating and non-cavitating flows.
Recently, it was proved that $C_v$ cannot be used as a single parameter in providing cavitation conditions and large inconsistencies regarding its determination in the previous reports exist [44]. Moreover, $C_v$ is not always detectable in HC devices because is too difficult to measure flow velocity or pressure where cavitation occurs (turbulent flow), especially when the complexity of the geometry of cavitating devices is increased [8].

3.2. HC types

Moreover, cavitation can be differently defined for different flow configurations. Three main classification families are attached cavitation, convected cavitation and vortex cavitation [32].

3.2.1. Attached cavitation

In attached cavitation, a wake or a region of separated flow filled with vapor can be observed. The cavity interface is partly attached to the solid surface. The liquid-vapor interface can be smooth and transparent or can have the shape of a highly turbulent boiling surface. Attached cavitation can be partial or appear as supercavitation when the cavity grows in such a way to envelop completely the solid body. This type of cavitation on a hydrofoil (Fig. 5 a) or on a propeller blade is usually termed “sheet cavitation”, whereas in the context of pumps it is known as “blade cavitation”. Moreover, in the context of bluff bodies (Fig. 5 b), a vapor-filled wake is often called as “fully developed” or “attached” cavity. Terms as “sheet”, “blade”, “fully developed” and “attached cavities” are usually used to indicate the same large-scale cavitation structure.

When the generated transient cavities are of the same order as the main attached cavity, attached cavitation is also called “cloud cavitation” in which a periodic formation and collapse of a “cloud” of cavitation bubbles can be observed. Fig. 6 shows the formation (Fig. 6 a), separation (Fig. 6 b) and collapse (Fig. 6 c) of a cavitation cloud on a hydrofoil oscillating in pitch. The temporal periodicity may occur naturally or it may be the response to a periodic disturbance imposed on the flow. A very common example of imposed fluctuations can be provided by the interaction between rotor and stator blades in pumps or turbines. Recently, the developed cavitation has been studied by Petkovšek et al. [45] in a shear induced HC reactor, where two facing rotors with special radial grooves were spinning in opposite directions: attached cavitation and bubbles shed from the attached cavitation have been seen on the solid surface of the teeth rotors, and in the gap between the rotor and the housing. A cavitation cloud between the aligned grooves has been also detected.

To effectively exploit the positive effect of HC, the developed cavitation should be studied and controlled in HC reactors. For instance, recently Dular et al. [20], studying a Venturi device where attached cavitation occurred [46], showed the progress of the developed cavitation (Fig. 7).

The authors observed that the flow followed a distinctive pattern where cavitation structures of different shapes and sizes were shed from the attached cavity. Due to the difference in pressure between the outer flow and the inside of the attached cavity, the streamlines curve towards the cavity and the surface beneath it. This caused the attached cavity to close and the formation of a stagnation point at which the flow was split into outer flow, which reattached to the wall, and the re-entrant jet, which travelled upstream, carrying a small
quantity of the liquid to the inside cavity. As the re-entrant jet travelled upstream, it lost momentum, turn upwards and “cut” the attached cavity, causing cavitation cloud separation (shedding). The cloud was then entrained downstream by the main flow and its collapse was observed where the pressure was recovered. During the separation, circulation around the structure can appear, causing it to reshape, break up, etc. In the meanwhile the attached cavity began to grow and the process is periodically repeated (Fig. 7 a). As the system pressure was decreased, and consequently the flow velocity was increased, a small cavity was extending and growing more and more (supercavitation phenomenon) (Fig. 7 b). Supercavitation flow is usually not accompanied by noise, vibration and erosion.

### 3.2.2. Convected cavitation

While in the attached cavitation the cavity interface is partly attached to the solid surface, in the convected cavitation the entire cavity interface is moving with the flow. Travelling cavitation bubbles are generated in the liquid for low-pressure gradients and move with it as they expand and collapse during their life cycles (Fig. 8).

### 3.2.3. Vortex cavitation

Flows characterized by high Reynolds numbers contain a region of concentrated vorticity where the pressure in the vortex core is often significantly smaller than in the rest of the flow and thus cavitation inception can occur. With a further reduction of the cavitation number, the entire core of the vortex may become filled with vapor. Fig. 9 shows some examples of cavitation vortices in a hydrofoil (Fig. 9 a), in a propeller (Fig. 9 b) and in a turbine (Fig. 9 c), respectively. It may happen that vortex cavitation bubbles remain smaller compared to the vortex core radius, with nearly spherical rapidly growing and collapsing bubbles entirely within the confines of the vortex core. However, at lower flow pressures the initially near-spherical bubble can expand and elongate to fill the core of the vortex and continue to grow along the vortex axis, becoming highly elongated [47].
4. Mechanisms of degradation of pollutants

The violent collapse of cavities in cavitating systems can result in the formation of reactive hydrogen atoms and hydroxyl radicals as well as can give rise to thermal hot spots, which can yield pyrolytic cleavage of chemicals [48]. Therefore, HC can have both chemical and mechanical effects into the system, Fig. 10.

The two main chemical mechanisms for the degradation of pollutants using HC are the thermal decomposition of volatile pollutant molecules entrapped inside the cavity during the collapse of the cavity and secondly, the reaction of $\cdot$H and $\cdot$OH radicals with the pollutant occurring at the cavity-water interface.

In case of non-volatile pollutants, the main mechanism for their degradation will be the attack of pollutants molecules by hydroxyl radicals at the cavity-water interface and in the bulk fluid medium.

Mechanical effects are also significant: (i) generation of shock waves by the collapsing cavity, (ii) liquid micro-jet formation, and (iii) creation of interfacial turbulence and powerful hydraulic shear stress due to the high flow velocity. Mechanical effects can directly rupture molecular bonds on the macromolecular main chain, especially the complex large molecular weight compounds, thus degrading the refractory organic matters. The broken down intermediates are more amenable to $\cdot$OH attack as well as biological oxidation, which can further enhance the rate of oxidation/mineralization of pollutants [43]. Further, the high velocity of the micro-jet (>100 m/s [33]) disturbs the boundary layer at the solid surface, leading to the breakdown of the liquid film responsible for the resistance to the mass transfer. Chemical and mechanical effects are also responsible for the enhancement of heat transfer, whose rate is almost two times more in presence of cavitation [49].

Recently, HC technique has been successfully applied in the field of wastewater to treat activated sludge, manure and biomass, resulting in an intensification and improvement of organic matter solubilisation. Cavitation acts by destroying bacterial cell walls and membranes resulting in a release of intracellular and extracellular matter [50,51]. Many of the intracellular constituents, including cytoplasm and nuclei acids, are readily biodegradable, resulting either in acceleration of both aerobic and anaerobic digestion processes in the sludge treatment or in promoting denitrification in wastewater treatment processes [9].
5. The effect of various parameters on HC effectiveness

Overall, a significant number of parameters exist that can affect HC effectiveness, influencing the number of generated (reactive) bubbles and collapse conditions. As showed in Fig. 11, an overview of the effective parameters in HC has been suggested by Braeutigam et al. [52].

The main factors that govern HC and its effectiveness are (i) device construction parameters, (ii) technological process parameters, and (iii) properties of the liquid [53]. The influence of all these aspects on HC effectiveness is separately analysed in the following paragraphs.

5.1. Construction parameters of cavitating devices

A first group of factors that can influence HC effectiveness include parameters that determine the structural characteristics of HC reactors, which consist of a cavitating inducer and a flow chamber.

5.1.1. Influence of geometry of cavitating devices

HC effectiveness depends on size and shape of cavitation inducer and flow chamber, which can both affect the number of cavitation bubbles and the collapse intensity. Recently, many researchers have focused on the optimization of geometry of cavitating devices to obtain the highest cavitational effects, in terms of both number of cavitation events and significant pressure drops, resulting also in a decrease in the energy required by the HC system. With this purpose, different HC devices have been developed. A first classification has been provided by Gogate et al. [54], and successively reported by Manickam and Ashokkumar [55], and adapted in this review:

a) **high pressure hydrodynamic cavitation reactor**, which is a high pressure positive displacement pump with a throttling device [54] or a blade [56] designed to operate at high pressure ranging from 50 atm to as high as 300 atm;

b) **low pressure hydrodynamic cavitation reactor**, where the flow through the main line is forced to pass through a geometric constriction, such as single-hole orifice or multiple holes on an orifice plate [8,52] (Fig. 12 a), a Venturi [15,43,44] (Fig. 12 b), a blade, and where the local velocities suddenly increase due to a reduction in the flow area resulting in lower pressures;

c) **low pressure swirling cavitation reactor**, where cavitation is generated by using a vortex flow swirl chamber [57] (Fig. 12 c) in which a central vortex is formed with a core pressure lower than the vapor pressure of the liquid thus inducing cavitation bubbles formation in the vortex, and where the liquid is then ejected from the chamber through the exit orifice into a volume of liquid where the cavitation bubbles collapse;

d) **high speed homogenizer**, which consist of rotating equipment (Fig. 12 d). Generally a roto-stator assembly is used [18], that operates at rotating speeds of 4000 rpm to as high as 20000 rpm, causing a pressure drop near the periphery of the rotor.
In the first three groups the energy needed to induce cavitation is fed directly through the liquid (static hydrodynamic cavitation devices) while in the fourth group the energy required is furnished by the help of a rotating inducer (dynamic hydrodynamic cavitation devices).

Further, different geometrical configurations of each device has been investigated. Following are discussed some examples of different HC reactors reported in literature.

Several researchers investigated the influence of the geometry of orifice plate systems on HC intensity [13,58], testing plates with different thickness [8,58] and with different numbers, shapes and sizes of holes [13,58,59]. It was observed that the highest cavitation intensity was generated by using the lowest free area in the orifice plate system. However, keeping constant the free area, orifice plates with higher diameter and lower number of holes showed lower intensities [11,13].

Šarc et al. [44] compared four very similar Venturi shapes, considering the same operating conditions (constant values for flow pressure, flow velocity, and temperature, respectively). Significant differences in typology, dynamics and intensity of cavitation were found. By using a high-speed camera, they observed how cavitation size and appearance could vary significantly when the divergence angle of the Venturi system was changed. Similarly, Kim et al. [15] investigated the effect of different Venturi outlet inclination angles on the performance of their HC system, which was used to increase sludge solubilisation. Rajoriya et al. [60] used a slit and a circular Venturi, respectively, to generate cavitation and, thus, to degrade Rhodamine 6G. Considering the same operating conditions, the degradation rate of the dye was marginally higher in the case of slit Venturi as compared to the circular one. In another study [61], the authors checked the influence of geometrical parameters such as total flow area, the ratio of throat perimeter to its cross-sectional area, throat shape and size, and configuration of the cavitating devices on decolorization of reactive blue 13 in aqueous solution. With this purpose, eight cavitating devices i.e. circular and slit Venturi, and six orifice plates having different flow area and perimeter were tested, showing that the HC efficiency was strongly influenced by the geometrical parameters. Carpenter et al. [62] provided a detailed geometrical analysis of HC devices in order to investigate the effect of geometry of orifice plates and Venturi of different shapes and geometrical parameters on the formation and stability of mustard oil in water nanoemulsion.

A swirling jet cavitation device has been investigated by Wang et al. [63] and Wang et al. [64]. Recently, Mancuso et al. [8,9] and Langone et al. [65] proposed an modified swirling jet-induced cavitation reactor, in which cavitation was generated by using a multiple-hole orifice plate able to generate multi-dimensional vortices which impact on a collision plate. The authors studied the influence of the injection slots number, the geometry of the system, and the number of HC devices in series on the HC effectiveness, highlighting how different geometries of the cavitating device influenced the HC effectiveness. A comparison between orifice plates and a vortex diode system on degradation of different organic solvents such as acetone, methyl ethyl ketone, and toluene was carried out by Suryawanshi et al. [66].

Badvve et al. [67] and Patil et al. [19] developed an efficient stator and rotor assembly, where rotor is a solid cylinder which has indentations on its surface, and can be rotated at different speeds of rotations. Afterwards, a novel stator and rotor configuration has been proposed by Petkovšek et al. [18] based on two facing rotors
with special radial grooves spinning in the opposite direction: the authors studied the effect of different shapes of the teeth of their rotor on the cavitation process [45]. Recently, another device, which can generate shear cavitation was proposed by Petkovšek et al. [18]. The main feature of this device is that it works not only as cavitation generator, but also as driving pump, avoiding additional pressure drop.

5.2. Technological process parameters

This second group includes parameters that are associated with the characteristics of the technological process, such as flow velocity or kinetic energy of the liquid, pressure at the inlet to the HC system, temperature of the liquid, pH of the liquid, and the HC “processing” time (the number of times the liquid passes through the cavitation region).

5.2.1. Influence of flow velocity

In an HC device, the number of cavitation bubbles is mainly related to an increase of the flow velocity or the kinetic energy of the liquid. Increasing the flow velocity, higher local pressure oscillations are expected, and pressure may fall below the vapor pressure of the liquid at the operating temperature, causing partial vaporization of the liquid and the generation of cavities. As can be deduced from Eq. 3, an increase in flow velocity implies a decrease in the cavitation number, resulting in an increase of cavitational effects. Higher flow velocities further can imply higher turbulence levels.

Flow velocity can be varied either by adjusting the pump flow rate (and thus the pressure at the outlet of the pump) or by changing the geometry of the cavitating device (i.e. reducing or increasing the constriction area). Šarc et al. [44] reproduced different cavitation conditions by varying the flow velocity at the throat of a Venturi system for different values of inlet pressure, while keeping constant the cavitation number and the geometry of their HC system. They observed that cavities slightly grew when the flow velocity was increased.

A Venturi system was used from Saharan et al. [43] to investigate the effect of the flow velocity on degradation of RR120 by increasing the inlet pressure from 3 to 10 bar. It was observed that the degradation rate increased with an increase in the inlet pressure reaching a maximum (5 bar) and then it dropped, due to the onset of the supercavitation. Similar results were reported by Prajapat and Gogate [68] and Gore et al. [69] using conventional Venturi systems.

Similarly, Joshi and Gogate [70] investigated the influence of flow velocity at the throat of a single orifice plate by varying the inlet pressure. In their experiments, inlet pressure was varied from 3 to 6 bar, by adjusting the flow rate. They observed that the extent of degradation of dichlorvos increased as the inlet pressure was increased from 3 bar to an optimum value of 5 bar. In this range, higher inlet pressures, and thus higher flow velocities, promoted an increasingly violent collapse of cavities, and thus an increasingly hydroxyl ions generation, resulting in an enhancement in the extent of degradation. However, at 6 bar the extent of degradation decreased due to the onset of supercavitation, resulting in an extremely rapid growth of bubbles downstream of the orifice plate with a subsequent splashing and vaporization of the flow.
Wang and Zhang [71] reported a continuous increase in the degradation rate of alachlor by using a swirling jet-induced reactor and increasing the flow velocity for the inlet pressure ranged from 2 to 6 bar, while keeping constant the geometry of their HC system. These results are in agreement with the study of Mancuso et al. [9] that, studying a modified swirling jet-induced cavitation reactor to improve the sludge disintegration, observed an increase in sludge disintegration degree by increasing the inlet pressure from 2 to 4 bar, due to an increase of flow velocity of the treated liquid. However, using the same HC device to treat a polluted dye aqueous solution by Rhodamine B, supercavitation occurred at an inlet pressure of 3 bar [16].

In a rotor-stator system, Badve et al. [72] varied the velocity of the liquid on the surface of the rotor by adjusting the rotational speed of the rotor. Their results showed that an increase in the rotational speed led to an increase in velocities of the liquid surface and to a decrease of the cavitation number.

Nevertheless, also the geometry can deeply influence the flow velocity, resulting in different cavitational effects. Sivakumar and Pandit [13], using multiple hole orifice plates and operating at the same inlet pressure, observed an increase in the cavitation process efficiency increasing the flow velocity for different geometries of their HC system. By using a swirling jet-induced reactor, Mancuso et al. [9] obtained an increase in HC effectiveness, in terms of activated sludge solubilisation, for the highest flow velocity achieved by decreasing the number of the injection slots at the same inlet pressure.

5.2.2. Influence of inlet pressure to the HC system

The inlet pressure can influence both the number of generated cavitation bubbles and their collapse intensity. In HC systems, an increase in inlet pressure always implies an increase in flow rate, and vice versa. As seen in section 5.1.1, higher inlet pressures involve higher flow rates and thus higher flow velocities, increasing turbulence levels and local pressure oscillations. Therefore, increasing the inlet pressure an enhancement of HC effectiveness is expected. Furthermore, higher inlet pressures involve higher pressure drops through HC devices. This increase in pressure can lead to higher shear forces that are able, especially for HC applications in WWTPs, to break down bacterial cell walls and to increase the release of organic matter [9,51]. However, at very high inlet pressures cavities can start coalescing with each other and supercavitation can be detected, resulting in a progressive decrease in the HC effectiveness. By using both a multi-hole orifice plate system and a swirling jet reactor, Mancuso et al. [8] observed that higher inlet pressures allowed to achieve higher extent of degradation rates in polluted aqueous solutions containing Rhodamine B. Similarly, Kumar and Pandit [73] found an increase in the pressure drop across their Venturi system due to higher inlet pressures to the HC system, resulting in an increase in the cluster collapse pressure. Rajoriya et al. [60], observed an increase in the decolorization rate of Rhodamine 6G with an increase in the inlet pressure up to an optimum value of 5 bar for both a slit and a circular Venturi system, and then it decreased beyond an optimum. The increase in decolorization rate with an increase in inlet pressure was attributed to the enhanced cavitational intensity due to more number of cavities that are formed at higher inlet pressure leading to the generation of more •OH radicals. On the other hand, at higher inlet pressure beyond an optimum, it was estimated that choked cavitation took place reducing the cavitation intensity due to partial collapse of cavities leading to lower degradation rates.
Similar findings were reported from Kumar et al. [74] that treated polluted aqueous solution by methylene blue dye by means of a Venturi system. In their experiments, the inlet pressure was varied from 1 to 10 bar, showing an optimum at 5 bar in terms of extent of dye degradation. Thanekar et al. [75] investigated the effect of inlet pressure on degradation of carbamazepine. The cavitational intensity increased with an increase in pressure from 3 bar until an optimum of 4 bar. Further increase in pressure beyond optimum value led to the formation of cavity cloud which in turn reduced cavitational intensity, resulting in a decrease in the extent of degradation. Carpenter et al. [62] used two Venturi systems and single orifice plates with different shapes in order to produce highly stable oil in water emulsion. For all devices, increasing the inlet pressure from 5 to 10 bar, a significant increase in HC efficiency was observed by the authors, but further increasing the pressure from 10 to 15 bar, only a marginal or no further increase in HC efficiency was observed. Choi et al. [76] tested different inlet pressure from 0.3 to 0.7 MPa for the degradation of bisphenol A. Again, the degradation rate increased from 0.3 to an optimum of 0.5 MPa, then, for a further increase in the inlet pressure, the downstream area into the Venturi system was completely filled with cavities, which began to coalesce with each other and formed a cavity cloud, resulting in a decrease in the extent of degradation. The effect of jet inlet pressure on the degradation of Rhodamine B was investigated by Tao et al. [77] over the range of 6-12 MPa. An increasing degradation rate for Rhodamine B at higher jet inlet pressure was observed from the authors. In this case, supercavitation was not detected simply because jet inlet pressure was not high enough or most likely due to the capacity of jets impingement to divide cavitation bubbles into micro-bubbles and then to prevent coalescence between them.

5.2.3. Influence of cavitation number

Cavitation number is inter-correlated with the other two parameters previously described: flow velocity and inlet pressure. Up to now, many studies on the influence of cavitation number on the effectiveness of cavitation have been carried out. However, missing or inaccurate information about the position at which the pressure and the flow velocity were measured or calculated implies that researchers commonly tend to use inappropriate values of cavitation number, taking advantage that there are no standard methods for its determination [44]. Most of the studies on HC are not repeatable because of a poor definition of the cavitation number in the manuscripts. Nevertheless, for completeness of the contents of this work, some results on the influence of cavitation number on the HC effectiveness have been reported.

Tao et al. [29] recently investigated the effect of the cavitation number on degradation of Rhodamine B by using a novel device based on double cavitating-jets impingement. A decrease in the cavitational number from 0.0486 to 0.0246 implied an increase in Rhodamine B degradation. However, in their results the authors reported that the pressure in the main chamber was just approximatively 0.1 MPa. This inaccuracy was due to the difficulty to get an accurate value of the pressure, and hence of the cavitational number (see definition of this parameter above in Eq. 3), most likely due to the presence of cavitational conditions that made measurements more difficult. As expected, Rajoriya et al. [61] observed a decrease in cavitation number with an increase of the inlet pressure for different geometries of their HC system in order to treat a polluted solution by reactive blue 13. In their study, it was found that the decolorization rate increased with a
decrease in cavitation number till an optimum value and then further decreased or remained constant for all the cavitating devices used, due to the inception of choked cavitation. Saharan et al. [43] used a Venturi system to degrade Reactive Red 120 dye. It was observed that the rate of degradation increased with a reduction in cavitation number, reaching a maximum and then dropping. In their findings, authors distinguished two different stages depending on cavitation number: firstly, a decrease in cavitation number led to an increase in the number of generated cavitation bubbles, resulting in an increase in the number of cavitation collapse pressure pulses as well as in the generation of more OH radicals that increased the degradation rate; then, the degradation rate decreased with further decrease in cavitation number. This may be because of reduced cavitational intensity due to excess numbers of cavities inside the Venturi system at very low cavitation number. Indeed, when there are too much cavities, these can start coalescing to form a larger cavitational bubble that can escape the liquid without collapsing or result into an incomplete collapse, resulting in a reduction of generated OH radicals.

Gore et al. [69] investigated the influence of the cavitational number, ranged from 0.210 to 0.095, on degradation of reactive orange 4 dye using a Venturi system. Also, in this case, it has been found that the decolourisation rate increased with a decrease in the cavitation number, reaching to the maximum at 0.15 and then decreased. Authors attributed these findings to an increase in the number of cavities and thus of the number of collapsing events, resulting in the generation of more OH radicals. However, a further decrease in the cavitation number below 0.15 implied a decrease in the extent of degradation due to the occurrence of choked cavitation/supercavitation conditions, where cavities no longer behaved as individual cavities. They coalesced with each other to form larger vaporous bubbles, which were carried away with the flowing liquid without collapsing.

Therefore, all studies confirm that for a decrease in cavitation number, an increase in the number of cavities is expected, resulting in an increase in overall collapse intensity of cavities. However, depending on the specific HC device configurations, after certain value of cavitation number, the number of cavities can become very high, so these cavities can start coalescing with each other and form a cavity cloud. Energy produced by the collapse of some cavities can be taken up by the neighbouring cavities, resulting in a cavity cloud formation (choked cavitation). Hence, the importance of optimizing HC cavitation devices in order to operate between these two limits, i.e. cavitation inception and choked cavitation/supercavitation, to get the maximum effect.

Further, it should be noted that in order to compare two or more HC systems each other, rather than cavitational number other parameters, such as for instance vibrations and noise measurements, and some indexes (see section 6) could be used to measure the intensity and efficiency of HC systems.

5.2.4. Influence of liquid temperature

The influence of temperature on HC is complex, which can have both positive and negative effects on HC treatment efficiency. Temperature affects the dynamics of cavities through the properties of the liquid such as vapor pressure, viscosity, surface tension, and gas solubility. As shown in the phase diagram of water (Fig. 2), the vapor pressure of a fluid depends on its temperature and it increases exponentially with temperature.
Thus, an increase in operating temperature can both enhance the probability of vaporous cavities generation due to entrapment of vapours and influence the kinetic rate. The increase of temperature implies a decrease of the viscosity and surface tension, leading to an easier bubble formation [53]. However, these generated bubbles are richer in vapor content, which reduce the intensity of bubbles collapse due to the “cushioning” effect of their implosion [53]. A rise in temperature reduces gas solubility, which is the chief source of cavity nuclei and thus reduces the rate of occurrence of cavitational events.

It is then likely that an optimum operating temperature might exist in specific conditions. When the temperature of the solution increases beyond the optimum value, the increase in vapor pressure of liquid might result in higher vapor content in cavitation bubbles leading to a cushioning effect and thus to an HC effectiveness reduction.

With this background, Wang and Zhang [71] have reported a positive effect on the degradation of alachlor with an increase in temperature from 30 to 40°C, but the degradation rate decreased with a further increase in the temperature over a range of 40 - 60°C. Joshi and Gogate [70] investigated the effect of operating temperature over the range of 31 - 39°C. In their experiments on degradation of dichlorvos, the maximum degradation rate was achieved at the lowest temperature. Mancuso et al. [9] investigated the influence of temperature, ranged from 20 to 35°C, on sludge disintegration. The authors observed that for this range of temperature, the higher the temperature, the more efficient HC (in terms of sludge solubilisation) was. Similar results were reported by Choi et al. [76] for the degradation of bisphenol A by using HC, where an increasing temperature from 10 to 50°C implied an increase in the extend of degradation. Šarc et al. [44] proved that the magnitude of pressure oscillations, which occurs due to cavitation bubbles collapse, increased for temperatures up to 40°C, but then dropped significantly for higher temperatures.

5.2.5. Influence of liquid pH

Typically, acidic or basic conditions are favourable to the degradation of chemical pollutants using HC reactors. The optimal pH value depends on the pollutants to be treated. Their degradation is strongly dependent on medium pH, as pH can influence the presence of •OH free radicals available for pollutants removal. Moreover, it is possible to get changes in pollutants structure for different pH, obtaining more biodegradable forms, which can be easily attacked by •OH free radicals. Usually, acid conditions are recommended for pollutants degradation by HC, because such conditions favours generation of hydroxyl radicals and impedes any reaction of recombination among free radicals [69].

Many studies have been carried out to remove dye pollutants from wastewaters. Saharan et al. [43] investigated the effect of pH on Reactive Red 120 dye degradation by carrying out experiments at different pH ranged from 2 to 11. Their results indicated that the rate of degradation increased with a decrease in the pH of the solution, confirming that acid conditions implied higher degradation rates for the Reactive Red 120 dye. Also Kumar et al. [74] observed a decrease in the rate of decolourization of polluted solution by methylene blue dye with an increase in the pH from 2 to 10, indicating that also the state of the molecules of this dye can change from ionic to molecular or vice versa depending on the solution pH and thus different rates of decolourization can be detected. These findings are in agreement with results of Rajoriya et al. [61],
where the authors investigated the influence of pH solution, ranged from 2 to 8, on decolourization of reactive blue 13 dye by using a slit Venturi to generate cavitation. Their results depicted that the extent of decolorization increased with a decrease in solution pH. Gore et al. [69] studied the effect of pH, ranged from 2 to 10, on degradation of reactive orange 4 dye using a Venturi system. The authors, starting from a neutral polluted solution, observed an increase in the decolourisation rate by either increasing or decreasing the pH of the polluted solution. However, the highest extent of degradation was obtained working at lower pH solutions, indicating a lower rate of recombination among generated •OH radicals in acid conditions and, hence, the presence of more •OH radicals available for the dye oxidation. Moreover, the increase in the degradation rate can be also attributed to the change of state of the orange 4 molecules from ionic to molecular under acidic conditions. This alteration in the state of the molecules makes them hydrophobic and more easily attacked by •OH free radicals. On the contrary, in the basic medium, the extent of degradation of orange 4 was not so high as in acid conditions because dye molecules remained in ionic state, resulting in an increase in their hydrophilic behaviour that implied their persistence in the liquid bulk.

Same findings have been reported by some researchers that studied the degradation of Rhodamine B. Mancuso et al. [8] treated polluted aqueous solutions by Rhodamine B using a multi hole orifice plate system, and observed the highest degradation rate of the dye at pH 2, while it dropped significantly and remained constant for pH ranged from 5 to 8. This was due to the prevalence in the acid conditions of Rhodamine B in the cationic form rather than the zwitterionic form [78]. Previous studies on Rhodamine B reported that the cationic form is easier to degrade [64], and thus at low values of pH the oxidation of Rhodamine B can be higher. Similar results were obtained by Mishra and Gogate [79] using a Venturi device, by Wang et al. [64] using a swirling jet-induced cavitation system, and by Tao et al. [77] using a novel reactor based on double-cavitating-jets impingement, respectively. A different trend of results on the effect of the pH was reported by Rajoriya et al. [60], studying Rhodamine 6G degradation. In this case, the observed results showed an increase in the extent of degradation with a pH increase in the solution from 2 up to an optimum value of 10. Then, the decolorization rate decreased. Under acidic pH Rhodamine 6G molecule became hydrophilic in nature, and thus, the dye remained in bulk of the solution where concentration of •OH radicals was minimum. On the other hand, under basic conditions Rhodamine 6G molecule became hydrophobic. Under such conditions, the dye was in its molecular state and located itself at the cavity-water interface where the concentration of •OH radicals was maximum. Recently, HC has been applied to treat water solutions contaminated with insecticide and pharmaceutical compounds, and the pH effect on pollutant degradation have been also investigated. Joshi and Gogate [70] investigated the influence of pH on degradation of dichlorvos, a household and public health fumigant. Using an orifice plate system as cavitating device, they found that lower pH provided higher extents of degradation. Studying the degradation of pharmaceutical compounds, Thanekar et al. [75] found that the efficiency of carbamazepine removal was maximum for a pH of 4 and minimum at 11. However, a decrease from 4 to 3 showed a worsening of the degradation process.

When treating activated sludge, it was observed that alkaline conditions were more suitable to enhance organic hydrolysis [80]. Optimal results in terms of organic matter release have been obtained when HC was
assisted with NaOH pre-treatment, then working at basic conditions with a pH of about 9 or 10, resulting in an increase in biogas production in the anaerobic digestion process [69].

5.2.6. HC schemes
Different schemes of HC experimental systems have been applied in the wastewater treatment field. As HC devices are generally able to transfer low power to the treated liquid, the most common experimental configurations used for HC applications are closed loop circuits, where the solution to be treated by HC, is treated and recirculated several time, for a certain processing time, to the HC reactor (Fig. 13) [8,13,20]. This scheme comprises a reservoir (1), a pump (2), control valves at appropriate places (V₁, V₂, V₃, V₄, V₅), a cavitation reactor (4), sampling ports (5) and measurement gauges (P₁, P₂). Control valves (V₁, V₂, V₅) are provided at appropriate places to control the flow rate through the mainline.

However, the full scale application of HC process in a wastewater treatment plant needs to move from closed loop to other configurations that allow a continuous treatment with a single pass, the so called “one-shot treatment” [81], without any recirculation of the solution to treat. This scheme can be implemented when the HC device is able to transfer high power during only one passage.

Concerning the closed loop circuit the HC efficiency and the extent of degradation increase significantly with the number of passages through the HC reactor. [8,82,83]. The increase in the number of passes increases the exposure time of pollutant to the cavitating conditions which results into higher extent of degradation [69]. If the inlet pressure is constant the number of passes is directly correlated with the process treatment time.

Save et al. [84] used an HC reactor based on throttling valves for the cells disruption and reported that an increase in the number of passes and time of treatment resulted in a corresponding increase in the extent of cell disruption. However, at low inlet pressures, the effect of the number of passes was marginal, but was slowly increased at higher inlet pressure.

5.3. Properties of the liquid medium
This last group includes parameters characterizing the properties of the liquid medium, mainly pollutant concentration, viscosity of the liquid, surface tension and dissolved gas content.

5.3.1. Influence of pollutant concentration
When cavitation conditions are constant, the amount of *OH radicals produced in the HC system should be constant as well. Therefore, for an increase in initial pollutant concentration, a decrease in pollutant removal rate is expected as hydroxyl radicals may not be sufficient to degrade the pollutant completely.

This is true in the case of removal of chemical pollutants dissolved in water solutions. Parsa et Zonouzian [58] studied the effect of the initial dye concentration on degradation of Rhodamine B by using a submerged multi hole orifice plate system. In their experiments, the initial dye concentration was ranged from 2 to 14 mg L⁻¹. They found that the efficiency of the process was inversely proportional to the initial dye concentration. In justifying this result, the authors explained that it might be imputed to an increase in the total amount of dye molecules, while the total amount of free hydroxyl radicals remained constant. These
findings are in agreement with other studies on degradation of Rhodamine B [8,64,77,85], Rhodamine 6G [60], reactive blue 13 [61], tetracycline [86], and other organic solvents such as acetone, methyl ethyl ketone, and toluene [66], respectively, where the authors observed an increase in the extend of degradation with a decrease in initial dyes concentration.

Treating activated sludge, the solid content (TS) concentration may influence the HC effectiveness, and thus the sludge disintegration degree. Kim et al. [15] investigated the influence of initial TS concentration, ranged from 5 to 40 g L⁻¹, on sludge solubilisation by using a Venturi system as cavitating device. The authors observed an increase in sludge solubilisation by increasing the initial TS concentration. These results are in agreement with the study carried out by Mancuso et al. [9], where the authors, ranging the initial sludge concentration from 7 to 40 g L⁻¹, observed the highest COD solubilisation for the highest initial sludge concentration. The increase in TS content provides more cells and aggregates and thus a higher viscosity of the sludge, due to the inter- and intra- particle interactions. Even if both growth and collapse of bubbles are slowed down by viscosity in HC [46], the increase in TS enhances the collisions between sludge flocs and cavitation bubbles, allowing the subsequent increase in sludge disintegration. Thus, the negative effect of high TS concentration on sludge degradation can be negligible if compared to the positive ones. In addition, the presence of solids can also influence the initial size of the nuclei. Therefore, the effect of initial bubbles radius must also be considered while choosing a particular liquid medium and process conditions [12].

5.3.2. Influence of liquid viscosity

Viscosity is the main characteristic reflecting the rheology of the treated matter. This important parameter can influence HC intensity and the way in which a polluted liquid flows into HC devices. Viscosity affects both the distribution of nuclei and the dynamics of bubbles. Usually, an increase in viscosity, in both Newtonian and non-Newtonian fluids, can reduce the efficiency of cavitation, resulting in a slowdown in both growth and collapse of bubbles[46]. In most of the applications, water is used as the liquid medium due to its low viscosity, which assists the occurrence of cavitation.

However, HC process has been used in fluids other than water. For instance, HC was used as a pre-treatment technique for activated sludge from wastewater treatment plants. In the activated sludge, the viscosity increases with an increase in TS concentration, due to the inter- and intra-particle interactions [15]. Experimental results showed that the negative effect of viscosity on the sludge solubilisation is negligible compared to the positive effect of sludge concentration for cavitation development [9,15].

Furthermore, it is interesting to underline that, when the activated sludge is treated by HC, its viscosity decreases indicating possible reductions in energy required from the anaerobic digestion heating, mixing, and pumping [87]. Kim et al. [15], using a Venturi system as cavitating device, observed that sludge viscosity decreased significantly during the first 30 min of treatment and then stayed relatively constant after 1h-treatment. In a full-scale application of the HC treatment, Garuti et al. [81] achieved a decrease in the range of 23 – 27% of the apparent viscosity of the treated agro-industrial sludge. The decrease in viscosity was mainly attributed to the increase in temperature, shear forces and cavitation bubble collapse. These results are in agreement with the study carried out by Mancuso et al. [9], where a swirling jet-induced cavitation
was used to increase the sludge solubilisation. During their HC tests, the authors observed that it was necessary to progressively reduce the frequency of the pump inverter in order to keep constant the inlet pressure, and thus the flow rate and flow velocity. Using the same experimental HC device for treating cattle manure, Langone et al. [88] proved that the apparent viscosity dropped about 21, 38, and 40% for samples HC treated at 6.0, 7.0, and 8.0 bars, respectively, as compared the untreated manure. This was due to a progressive alteration of the rheology of the activated sludge, resulting in a decrease of its viscosity during the HC treatment. Similarly, Prajapat and Gogate [68] investigated the effect of inlet pressure on depolymerisation of aqueous polyacrylamide solutions by using a Venturi system. Their experimental results showed an increase in intrinsic viscosity reduction with an increase in inlet pressure. Mohod et al. [89] used an high speed homogenizer for the intensification of biodiesel production. In their study, the combination between HC and the increase in temperature till an optimum resulted in reduced viscosity of the oil phase and enhanced miscibility of the reactants that drove the observed increase in the yield of biodiesel.

5.3.3. Influence of surface tension

Surface tension has an effect on the nucleation stage of the HC process by controlling the number and the size of stable gas or vapor nuclei that are present in the liquid, which influence the HC process efficiency [54]. For a bubble at stable equilibrium with the surrounding liquid, pressure inside the bubble is equal to the sum of external liquid pressure and surface tension forces. Before being subjected to cavitation, the higher the surface tension, the faster will be the dissolution of the gas nuclei into the liquid due to surface tension forces and the smaller will be the number of gas nuclei present in the liquid at any instant. Thus, at the very beginning of the HC process, nuclei may not be present in sufficient numbers to get any significant impact on cavitation. However, during the collapse, cavities become fragmented at high implosive velocities and these fragments can subsequently become nuclei for the next cycle. Thus, over a period of time, nuclei become sufficient in number and cavitation effects can be observed.

The surface tension depends on the type of liquid and temperature; a rise in temperature causes a fall in the surface tension, which means easier evaporation [53]. The presence of a small amount of surfactant can reduce the surface tension and thus to greatly reduce the cavitation threshold, resulting in an easier generation of bubbles and, therefore, of hydroxyl radicals.

However, while a decrease in the surface tension of the liquid can imply an easier generation of cavitation, it should also be noted that a decrease of surface tension can affect the collapse of cavities, which would be less violent.

5.3.4. Influence of dissolved gas content

The presence of dissolved gases can significantly enhance cavitation effects by supplying nuclei for the HC process; in addition, the quantity of the gas inside the cavity can significantly affect the final collapse temperature and pressure [54]. Most of the HC applications are carried out in the presence of gas atmosphere; however, the effect of presence of various gases (i.e. argon, air) has also been investigated [90]. It was
observed that different properties of dissolved gases, such as the gas solubility, can significantly affect the cavitation process [54].
6. **HC combined to advanced oxidation processes (AOPs)**

As discussed above, HC has a potential in degrading organic pollutants effectively to a certain level. The efficiency of the process depends on the typology of pollutants to be treated, operating conditions, number of hydroxyl radicals that are being generated and their effective utilization. Hence, in this regard, various researchers have investigated on the synergetic effect of HC coupled with AOPs such as \( \text{H}_2\text{O}_2 \), \( \text{O}_3 \), Fenton’s reagents, photocatalysis, etc. in order to improve the efficiency in terms of increase in \( \cdot \text{OH} \) radicals generation and their effective distribution. These combined methods have shown higher efficiencies when compared to HC or other AOPs techniques used as individual operation.

Table 1 depicts some of the applications of HC combined with existing AOPs for the wastewater treatment illustrating the typology of pollutants, used equipment, operating parameters and removal efficiencies. Further, some researcher have also investigated on the synergetic effect of HC in presence of additives in combination with other techniques such as acoustic cavitation [91] and ultraviolet irradiation [75].
7. Methods to evaluate the efficiency of cavitation

In the last years, in order to investigate the efficiency of different HC systems in terms of both treatment removal efficiency and total energy supplied to the system, many methods have been proposed, depending mainly upon the treated matter characteristics.

7.1. Pollutants degradation in wastewaters

HC technique has recently been used alone or in presence of additives to degrade toxic and carcinogenic compounds in polluted water bodies. In different studies, the degree of the degradation of pollutants, such as for Rhodamine B (RhB) and Rhodamine 6G (Rh6G) [8,13,64,79,85], orange 4 dye, orange acid II [92], brilliant green [92], reactive brilliant red K-2BP [93], methylene blue (MB) dye [74], pharmaceuticals [94] and pharmaceutical micro-pollutants [94,95] has been evaluated by considering the extent of degradation (ED), as a percentage of removal. ED can be calculated as reported in Eq. 4:

\[
ED(\%) = \left( \frac{c_0 - c}{c_0} \right) \cdot 100 \quad \text{Eq. 4}
\]

where \(c_0 \, [\text{mg L}^{-1}]\) is the initial pollutant concentration and \(c \, [\text{mg L}^{-1}]\) is the residual pollutant concentration at the generic instant. All studies reported that for higher ED, higher HC efficiencies, in terms of extent of pollutant degradation, have been observed.

Another parameter that has been taken into account is the cavitation yield C.Y. [8,13,64,69,92,96], calculated as reported in Eq. 5 and defined as the ratio of the observed cavitation effect, in terms of amount of degraded pollutant (usually expressed in mg L\(^{-1}\)) by using HC, to the total energy supplied to the system:

\[
\text{C.Y.} = \left( \frac{\text{Degraded matter}}{\text{Power density}} \right) \quad \text{Eq. 5}
\]

where the degraded matter is the amount of pollutant [mg L\(^{-1}\)] removed during the HC treatment, while the power density, [J L\(^{-1}\)], is represented by the following equation Eq. 6:

\[
\text{Power density} = \frac{P_{\text{abs}} \cdot t}{V} \quad \text{Eq. 6}
\]

where \(V\) is the volume of the treated matter [L], \(P_{\text{abs}}\) is the pump absorbed power by the HC system [W] and \(t\) is the treatment time [sec]. Higher C.Y. imply higher HC efficiencies, in terms of both degradation and total energy supplied to the HC system.

Treating the same pollutant, C.Y. can be used to compare two or more different HC systems with each other. On the contrary, treating different contaminants with different HC systems, it is not possible to make a comparison between their treatment efficiencies because of the different properties and molecular structures of pollutants, which can provide a different resistance to the HC treatment.
7.2. Biological wastewater treatments

In the field of biological treatments, HC efficiency can be evaluated by measuring (i) the improvement of solubilisation of the activated sludge in terms of soluble chemical oxygen demand (SCOD) increase, Eq. 7, (ii) the ratio of change in soluble chemical oxygen demand (SCOD) after cavitation to particulate chemical oxygen demand \( \left( \text{PCOD}_0 = \text{TCOD} - \text{SCOD}_0 \right) \), Eq. 8, and (iii) the ratio of change in ammonia after cavitation to initial organic nitrogen content \( \left( \text{Norg}_0 = \text{TKN}_0 - \text{NH}_4^+ - \text{N}_0 \right) \), Eq. 9:

\[
\Delta \text{SCOD} \% = \frac{\text{SCOD}_{\text{cav}} - \text{SCOD}_0}{\text{SCOD}_0} \times 100 \\
\text{DD}_{\text{PCOD}} \% = \frac{\frac{\text{SCOD}_{\text{cav}} - \text{SCOD}_0}{\text{PCOD}_0}}{\frac{\text{SCOD}_{\text{cav}} - \text{SCOD}_0}{\text{TCOD} - \text{SCOD}_0}} \times 100 \\
\text{DD}_n \% = \frac{\frac{\text{NH}_4^+ - \text{Norg}_0}{\text{Norg}_0}}{\frac{\text{NH}_4^+ - \text{Norg}_0}{\text{TKN}_0 - \text{NH}_4^+ - \text{N}_0}} \times 100
\]

where \( \text{SCOD}_{\text{cav}} \) is the soluble COD of the treated sludge by using HC [mg L\(^{-1}\)] at the time \( t \), \( \text{SCOD}_0 \) is the soluble COD of the untreated sludge [mg L\(^{-1}\)], \( \text{TCOD} \) is the total COD of the untreated sludge [mg L\(^{-1}\)], \( \text{NH}_4^+ - \text{Norg}_0 \) is the ammonia content of the treated sludge by using HC [mg L\(^{-1}\)] at the time \( t \), \( \text{NH}_4^+ - \text{N}_0 \) and \( \text{TKN} \) are the ammonia and total Kjeldahl nitrogen content of the untreated sludge [mg L\(^{-1}\)].

Another important index reported in different studies on sludge disintegration is the sludge disintegration degree calculated as the ratio of SCOD-increase by cavitation to the SCOD-increase by the chemical disintegration, Eq. 10:

\[
\text{DD}_{\text{COD NaOH}} \% = \frac{\text{SCOD}_{\text{cav}} - \text{SCOD}_0}{\text{SCOD}_{\text{NaOH}} - \text{SCOD}_0} \times 100
\]

where \( \text{SCOD}_{\text{NaOH}} \) [mg L\(^{-1}\)] is the soluble COD of the reference sample obtained with a strong alkaline disintegration (NaOH digestion).

Further, HC efficiencies should be referred to other indexes that consider the energy consumption in each HC system. Many studies report the specific supplied energy (SE), defined as the energy required by the HC system to the initial amount of total solids Eq. 11:

\[
\text{SB} \left( \frac{\text{kJ}}{\text{kgTS}} \right) = \frac{P_{\text{abs}} \times t}{V \times \text{TS}}
\]

where \( P_{\text{abs}} \) is the power absorbed from the pump [W], \( t \) is the treatment time [sec], \( V \) is the volume of the treated sludge [L] and \( \text{TS} \) is the activated sludge solids content [g L\(^{-1}\)].

Similarly, the energy efficiency (EE), expressed as mg DSCOD kJ\(^{-1}\), has been calculated as the mg of SCOD-increase per unit of energy supplied, Eq. 12, [97]. Higher EE values correspond to higher removal efficiencies.

\[
\text{EE} \left( \frac{\text{mg} \Delta \text{SCOD}}{\text{kJ}} \right) = \frac{V \times \Delta \text{SCOD}}{P_{\text{abs}} \times t} \times 1000
\]
8. Modeling

In the past years, HC has been deeply studied by many researchers worldwide. As reported in the previous sections, it was observed that essential parameters and operating conditions can deeply influence cavitation intensity and the way in which it is generated. Due to both turbulent flow in cavitation conditions and complexity of the geometry of cavitating devices, some of these parameters such as flow velocity and flow pressure are always more often difficult to measure. As observed by Šarc et al. [44], large inconsistencies in defining values of these parameters in the scientific reports exist. Then, only an accurate measurement of these variables could lead to repeatable results. However, it was observed that flow velocity and flow pressure measurements can be easier made in simpler geometries such as hole orifice plates, nozzles or Venturi systems. On the contrary, in cavitating devices with a more complex geometry, it is rather difficult to perform measurements on these variables, resulting in an incomplete or incorrect characterization of the cavitation process.

For this reason, in the last years there is an increasingly interest in developing mathematical models with the main goal to define a powerful tool able to provide information on hydraulic parameters and on the fluid dynamics into cavitating devices. Many researchers are then focusing on mathematical modeling of different HC devices such as orifice plates, nozzles, Venturi, swirling jet or rotor-stator systems. Numerical investigations have been conducted to predict cavitation and to determine whether computational methods can be used as a reliable tool to evaluate the performance characteristics of the cavitating devices. However, also the definition of the mathematical problem can be difficult because it can include very complex geometries of HC devices in addition to the presence of turbulent conditions in the fluids.

Recently, Mancuso [98] implemented a three-dimensional Computational Fluid Dynamic (CFD) analysis of a swirling jet reactor in order to gain a better understanding of fluid dynamics into the reactor. In his work, the author investigated on the effect of different geometries of the reactor, by considering different diameters of the injection slots of the reactor, on flow velocity and flow pressure distributions.

Palau-Salvador et al. [99] performed numerical predictions of cavitation flows based on CFD for simple geometries, such as orifices, nozzles and Venturi systems, using the commercial CFD code FLUENT 6.1.

Pawar et al. [100] attempted to make a comparative assessment of cavitation yield of four cavitation devices with different flow geometries (three Venturi and one orifice plate). With this main purpose, a fourfold approach was adopted for comparative assessment, viz. CFD simulations of cavitating flow using FLUENT 6.3, simulations of individual cavitation bubble dynamics using diffusion limited model, high speed photographs of cavitating flow in down-stream region of cavitation devices and a model reaction of KI oxidation to liberate iodine. Navickas and Chen [101] studied cavitating Venturi internal flow characteristics by means of the three-dimensional fluid flow program, FLOW-3D. Their results indicated that numerical methods are effective in obtaining relative magnitudes of significant parameters affecting the performance of the cavitating device. In order to optimize a multi-hole injector nozzle, He et al. [102] modelled the three-dimensional nature of the flow in the nozzle investigating the effect of the geometry and dynamics factors on
the spray characteristics in cavitating conditions. Müller et Kleiser [103] developed a numerical method for the vortex breakdown in a compressible swirling jet non-cavitating flow. Ashrafi and Ghasemi [104] performed an experimental and numerical investigation on the performance of small-sized cavitating Venturi. Badve et al. [72] made a mathematical model describing the shear rate and pressure variation in a complex flow field created in a rotor-stator type HC reactor.

Thanks to the quick development of computational resources, there have been attempts to model the flow unsteadiness during cavitation using the Large Eddy Simulation (LES), which present an alternative way of improving qualitative and quantitative aspects of complex turbulent flow predictions for both research and engineering purposes. LES can explicitly simulate the large scale of a turbulent multiphase flow while modeling the small scales. Despite some yet unresolved issues, LES is currently considered the most promising method for studying complex multiphase flows. Moreover, numerical results of studies on HC by using LES have showed a very good agreement between mathematical models and the experimental data [103,104].

Therefore, an accurate mathematical model could be a useful tool to optimize parameters, operating conditions and geometry of the cavitating device with the main aim to improve cavitating devices performances in terms of generated cavitation intensities.
9. Concluding comments

HC technology appears to be very effective for intensification of chemical and mechanical processing in the specific area of wastewater treatment. Among mechanical treatments, HC process is taking a more prominent role, mainly due to the ease of operation, flexibility and capability to vary the required intensities of cavitational conditions.

In the present work, the importance of the HC phenomena in wastewater treatments engineering has been exemplified, explaining the basic principles of the process and critically examining the aspects related to the use of different types of HC. The efficiency of the HC process has been reported as function of several parameters that characterize HC devices and the wastewater to be treated. The optimum selection of the HC device and of the operating parameters will help to obtain more overall advantages for specific applications. According to the reviewed literature, there is still no fully comprehensive method to evaluate the efficiency of HC. However, some main methods commonly used for this purpose have been reported.

This work provides a useful guideline for HC applied to wastewater treatment and acts as a starting point for the HC process optimization. Moreover, the provided framework could form an origin for future literature studies, focusing on several aspects, among them modeling. Mathematical models can be used as useful tools to gain a better understanding of how HC devices operate in cavitating conditions and, further, to optimize performances of these devices in terms of cavitational effects.
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