NRC Research Press

REVIEW

Wastewater remediation via controlled hydrocavitation

Rosaria Ciriminna, Lorenzo Albanese, Francesco Meneguzzo, and Mario Pagliaro

Abstract: Controlled hydrodynamic cavitation is an energy- and chemicals-saving technology increasingly applied to water sanitation and wastewater remediation via mechanical, oxidative, and thermal degradation of chemical and biological pollutants, including recalcitrant contaminants. Reviewing the advances that have allowed hydrocavitation to emerge as an economically and technically viable environmental technology, we identify the key design parameters that decide its efficacy in degrading biological and chemical contaminants. The ongoing renewable energy boom, lowering the cost of electricity across the world, will only accelerate the adoption of hydrodynamic cavitation as an eminent technology of our common path to sustainability, with energy and clean water access for all.

Key words: controlled hydrodynamic cavitation, hydrocavitation, wastewater, water treatment.

Résumé : La cavitation hydrodynamique contrôlée est une technologie énergétique et d'économie de produits chimiques appliquée de plus en plus dans le domaine de l'assainissement de l'eau et de la remédiation des eaux usées par la dégradation mécanique, oxydative et thermique des polluants chimiques et biologiques, y compris des polluants récalcitrants. En passant en revue les progrès qui ont permis à l'hydrocavitation de se distinguer comme une technologie de l'environnement économiquement et techniquement viable, nous dégageons les paramètres clés de conception qui déterminent son efficacité en matière de dégradation de contaminants chimiques et biologiques. L'essor de l'énergie renouvelable en cours, baissant le coût d'électricité à travers le monde, ne fera qu'accélérer l'adoption de la cavitation hydrodynamique comme une technologie éminente dans notre démarche commune vers la durabilité, avec l'accès à l'énergie et à l'eau propre pour tous. [Traduit par la Rédaction]

Mots-clés : cavitation hydrodynamique contrôlée, hydrocavitation, eaux usées, traitement de l'eau.

Introduction

Clean water and sanitation is one of the 10 main sustainable development goals of the United Nations, aiming at halving the amount of untreated wastewater globally by 2030, while minimizing the use and release of hazardous materials (Sustainable Development Goals 2015). Water, life's essential resource, is also an exceptional transport media with huge storage capacity for harmful chemical and biological species obtained by diverse anthropogenic activities (Shannon et al. 2011). Agriculture uses water for irrigation. Industry uses water as a raw material, as well as a washing, transporting, diluting, cooling and heating agent. Urban communities use water mostly for drinking, washing, and as carrier of human excreta. An increase in urbanization, agricultural and industrial production, along with rising living standards and increasing population, explains why water management is amongst the main UN sustainable development goals.

In general, wastewater, including both urban sewage, agricultural and industrial effluents, needs to be effectively treated via chemical and biological degradation processes prior to the discharge of the purified water into the environment or its recycling and reuse (Ranade and Bhandari 2014). Conventional wastewater treatment consists of three main steps (digestion, settling, dewatering) followed by slow anaerobic digestion processes (Kumar and Pandit 2012). Electricity demand is significant, with effluent treatment plants using traditional extended aeration absorbing 50% more power than anaerobic sludge digestion. Furthermore, a harmful amount of nitrogen and phosphorus compounds are often released into the environment as a result of treatment, building up as "nutrients" in sea or lake water and causing algal blooms and overgrowth of cyanobacteria (blue-green algae), with consequent rapid deoxygenation due to algal decomposition by bacteria (eutrophication) (Chislock et al. 2013).

Progress in the last three decades to find better and less expensive wastewater cleaning strategies has been relatively slow, while new needs such as the removal of low-levels of pharmaceuticals and other micropollutants have emerged (Nam et al. 2014). In Europe, for instance, the recently established EU-funded European Innovation Partnership on Water aims to facilitate the development of innovative solutions to de-couple economic and industrial growth from the actual water use, by developing new solutions to radically reduce its consumption and eventually achieve near-zero discharge of water by using closed-loop systems (European Innovation Partnership on Water 2016).

Among the most promising new approaches, controlled hydrodynamic cavitation (HC) triggered and sustained by devices designed to drive and control the formation, growth, and subsequent collapse of vapor-filled or even void cavities in water, is emerging as an economically and technically feasible alternative to degrade and eventually mineralize harmful chemical and biological pollutants via advanced oxidation processes (AOPs) (Dular et al. 2016).

Reviewing progress in 2005, Pandit, who along with Gogate has pioneered the field in India since the early 1990s, concluded that the "dream to realize industrial scale applications of the cavitational reactors" was about to realized (Gogate and Pandit 2005). Indeed, ten years later he could describe the first industrial applications of the hydrocavitation technology, including pigment

Received 21 July 2016. Accepted 31 October 2016.

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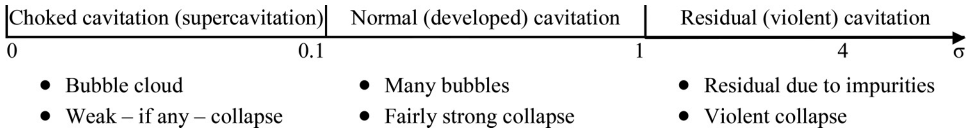
Published at www.nrcresearchpress.com/er on 1 November 2016.

Fig. 1. Main controlled hydrodynamic cavitation regimes based on the cavitation number (σ).



particle reduction and chemical oxygen demand (COD) abatement in chemical industry's effluents (Pandit 2016). Hydrodynamic cavitation, as emphasized by Michel and Kozyuk (2014), is "a process tool for sustainable future". Yet, the huge potential of HC in cleaning and sanitizing water on a global scale is far from being fully realized.

Following a summarized review of the basics and advances in hydrodynamic cavitation applied to water purification, in this study we aim to show through selected representative examples and critical arguments why this technology will play a central role in our common path to sustainable development, largely based on circular economy (Haas et al. 2015) and renewable energy sources.

Hydrodynamic cavitation

Contrary to acoustic cavitation (AC) in which the formation, growth, and implosive collapse of cavitation bubbles is caused by the propagation of ultrasonic waves (Mason and Peters 2002), in hydrodynamic cavitation the same phenomena are produced by the motion of fluid, with all liquid being forced through an aptly developed cavitation reactor (Venturi tube, orifice plate, rotor-stator, and others).

Constrictions and nozzles, resulting in acceleration and local depressurization, alter the flow geometry. If the pressure falls below the boiling point, water vaporizes and vapor bubbles are generated. Although hydrodynamic cavitation can be numerically described by means of the Rayleigh–Plesset equation of bubble dynamics along with other diffusion, balance, and continuity equations (Moholkar and Pandit 2001; Capocelli et al. 2014; Zamoum and Kessal 2015), for the purposes of the present study different hydrodynamic cavitation regimes are practically identified according to the values assumed by a single dimensionless parameter, i.e., the cavitation number σ derived from Bernoulli's equation, shown in its simplest form in eq. (1).

$$(1) \qquad \sigma = (P_0 - P_v)/(0.5 \cdot \rho \cdot u^2)$$

where P_0 (Nm^{-2}) is the average pressure downstream of a cavitation reactor, such as a Venturi tube or an orifice plate, where cavitation bubbles collapse, P_v (Nm^{-2}) is the liquid vapor pressure (a function of the average temperature for any given liquid), ρ (kg m^{-3}) is the liquid density, and u (ms^{-1}) is the flow velocity through the nozzle of the cavitation reactor.

In the following, only works adopting the definition of the cavitation number as per eq. (1) will be mentioned. Indeed, a thorough discussion of the issues raised by the use of the cavitation number as per eq. (1) has been recently published by Šarc and co-workers in Slovenia (Šarc et al. 2017). The team has shown that by changing the very definition of the different parameters included in the expression for σ can lead to differences in its resulting values as large as two orders of magnitude. In particular, the pressure P_0 and velocity u are not always measured, respectively, downstream of the cavitation constriction and through it. While little doubt exists that the velocity measurements should always be referred to the fluid motion through the nozzle, sometimes, quite bizarre choices were made for the location of pressure gauges. Scientists in Japan have recently shown that the control of the downstream pressure allows to obtain and describe the most relevant and desired features of hydrodynamic cavitation (Soyama and Hoshino 2016).

Gogate and co-workers identify three intervals in the range of values assumed by the cavitation number, corresponding to broad cavitational regimes (Gogate 2002; Bagal and Gogate 2014). Accordingly, Fig. 1 shows the typical controlled cavitation regimes through a nozzle nested into a hydraulic circuit, which can at least provide an early practical guidance.

As mentioned above, cavitation occurs whenever the pressure of the fluid crossing the cavitation reactor (vena contracta) falls below the vapor pressure at the given temperature. The lower the cavitation number, the higher is the energy dissipation due to the friction produced by the formation of more widespread vapor bubbles. Ideally, without impurities and dissolved gases, cavities would be generated for values of σ below 1 (or another threshold value depending on the specific setup). Indeed, more subtle and yet very significant effects, modulating the cavitation inception, extent, and intensity, arise from the reactor's geometry, the upstream flow rate (in turn connected with the upstream pressure, i.e., the geometry and mechanical power of the impellers), and the medium temperature as well its gas and solid particles content.

The first practical application of controlled hydrodynamic cavitation, developed in Russia in 1977, was in the supercavitation (chocked) regime created by conic torpedoes capable of travelling underwater at speeds in excess of 370 km/h, or five to six times the speed of a normal torpedo, due to greatly reduced drag upon formation of a large gas bubble enveloping the torpedo created by outward deflection of water by the nose cone (Ashley 2001).

In 1990, Yan and Thorpe in the UK established the basics of supercavitating flows through an orifice, finding that in this context the threshold value of the respective cavitation number from eq. (1) is fairly unambiguous for any given size of the reactor, being independent of the liquid velocity and depending only on the ratio of the orifice diameter to the pipe diameter. Moreover, during continuous supercavitation, values of σ were shown to accurately correlate with the size of the quasi-steady gas bubble (Yan and Thorpe 1990). However, applications of the supercavitation regime to water sanitation were long ignored until recently, when Dular and Šarc reported that it is the most effective HC regime for the removal of certain strains of bacteria and likely the most effective across several known technologies (Dular et al. 2016; Šarc et al. 2016).

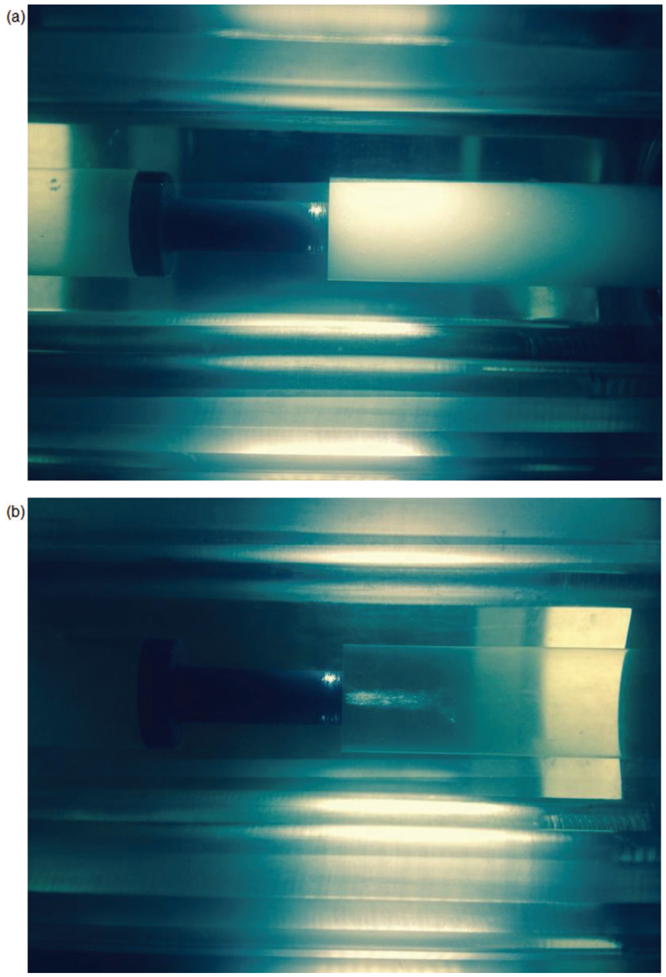
Controlled hydrocavitation

In general, the technical and scientific advances that opened the route to today's HC devices designed to produce only controlled occurred in the mid and late 1990s, when Kozyuk in Ukraine (and later on in the US), Pandit in India, and Chahine in the US developed the cavitation devices and established the conditions to control the hydrocavitation phenomenon, so that energy dissipation takes place in a small volume giving rise to a spatially concentrated energy peak.

This enables controlled cavitation (controlling the location, size, density, and intensity of cavity implosions), rather than destructive uncontrolled cavitation, thereby protecting the equipment from fast physical and chemical deterioration (Fig. 2).

In detail, Pandit in 1999 modeled hydrodynamic cavitation using the concept of cavity cluster of cavitation, rather than a single cavity in isolation, to depict a more thorough picture capable of explaining the effect of operating variables and equipment geometry on two different modes of cavitation generation (Venturi tube and high-speed homogenizer) (Kumar and Pandit 1999). The

Fig. 2. (*a*) Uncontrolled bubble collapse and (*b*) controlled bubble collapse. [Image courtesy of Arisdyne Systems, Reproduced from (Reimers 2015), with kind permission]. [Colour online.]



outcome was a design algorithm called HyCator, used since 2005 by India-based HyCa Technologies to manufacture tailor-made hydrocavitation reactors producing targeted cavitation bubbles to meet specific customer needs with respect to the intensification of physical and chemical processes.

Independently, Kozyuk developed the shape of the internal baffle body and the conditions (ratio of the cross-sectional portion of the hydrodynamic flow in the local constriction to the cross-sectional portion of the flow in the channel < 0.8) for coordinated collapse of groups of cavitation bubbles in a local volume along with the formation of high-energy three-dimensional shock waves whose propagation intensifies the collapse of groups of cavitation bubbles (Kozyuk 1997, 2016).

Similarly, Chahine relied on his background as naval engineer using a bluff body (a body that, as a result of its shape, has separated flow over a substantial part of its surface) to develop jet nozzles (tradenamed as DynaJets) that generate cavitation at lower pressures through the bluff body and swirling flow (Chahine 2001). This configuration raises the local velocity of the fluid in the jet shear layer as close to the nozzle exit as possible, through the creation of vortices in the exit flow between the exiting fluid jet and the surrounding quiescent liquid.

Finally, Martynenko and co-workers in Canada recently developed a mechanical variant to an ordinary Venturi tube cavitation reactor after inserting symmetrically arranged, small section recirculation pipes, connecting the main pipe just upstream of the nozzle to the nozzle itself (Martynenko et al. 2015). Using only the naturally occurring pressure gradient, this configuration focuses the cavitation area, increases the intensity of the process, and reduces noise.

While non-stationary HC reactors, such as rotational generators, have been successfully developed and applied, Venturi-type stationary reactors still appear as the most appealing candidates for industrial-scale applications due to their intrinsic ease of construction, scaling and replicability, which along with low-cost, establish decisive advantages over orifice plates running the risk of obstruction from solid particles and other viscous substances (Albanese et al. 2015).

The energy transfer efficiency of HC reactors, i.e., the ratio of the power dissipated in the liquid to the electric power supplied to the system, is significantly higher (about 60%–70%, depending on the operating conditions) than that of ultrasonic (acoustic) reactors (only about 10%–40%), the energy efficiency itself of HC reactors growing with their scale (Gogate et al. 2001; Langone et al. 2015). Furthermore, compared to AC cavitators, HC reactors seem to be more suitable for industrial applications due to wider area of cavitation, much lower equipment cost, and more straightforward scalability.

Chemical effects of hydrocavitation

A seminal investigation of single-bubble and multi-bubble sonoluminescence enabled Yasui and co-workers in Japan to show that the temperature and pressure inside a collapsing bubble increases dramatically up to 5000–10 000 K and 300 atm (1 atm = 101.325 kPa), respectively, due to work done by the liquid to the shrinking bubble, while luminescence is generated by plasma created inside the cavitation bubbles and (or) by the recombination of ·OH radicals (Yasui et al. 2004). In general, hydroxyl radicals are only formed if the interior temperatures of the collapsing bubbles are > 2500 K, that is, if the cavitation is intensive enough. When this is the case, in the collapse of the cavitation bubble "almost all water vapor molecules inside a bubble are dissociated by high temperature at the end of the bubble collapse and many chemical products such as H_2, O_2, and OH are created inside a bubble" (Yasui et al. 2004).

More recently, the H_2O decomposition by hydrodynamic cavitation leading to the generation of powerful oxidant hydroxyl radicals ·OH (eq. 2) with oxidation potential 2.80 eV, has been thoroughly described along with the consequent cascade of further reactions involving, among the others, recombination into hydrogen peroxide, formation of $HO_2\cdot$ peroxyl radicals, and increase of dissolved oxygen concentration (Batoeva et al. 2011; Aseev and Batoeva 2014; Rajoriya et al. 2016, 2017):

$$\text{(2)} \qquad H_2O \rightarrow H\cdot + \cdot OH$$

$$\text{(3)} \qquad H\cdot + H\cdot \rightarrow H_2$$

$$\text{(4)} \qquad \cdot OH + \cdot OH \rightarrow H_2O_2$$

$$\text{(5)} \qquad \cdot OH + H_2O_2 \rightarrow HO_2\cdot + H_2O$$

$$\text{(6)} \qquad \cdot OH + HO_2\cdot \rightarrow H_2O + O_2$$

$$\text{(7)} \qquad HO_2\cdot + H_2O_2 \rightarrow \cdot OH + H_2O + O_2$$

While a direct measurement of the concentration of ·OH radicals is hardly possible due to their high reactivity and, consequently, extremely short lifetimes, few experiments demonstrate that HC processes indeed produce hydroxyl radicals. One such indirect proof was derived using benzene as a chemical dosimeter (when the interaction of ·OH radicals and the benzene molecules occurs inside the bubble or at the gas–liquid interface), observing the formation of significant amounts of phenol (10 μmol L^{-1}) after 60 min of HC treatment (Batoeva et al. 2011). The same team in Russia subsequently showed the HC efficacy in generating additional hydroxyl radicals after adding hydrogen peroxide and observing its concentration decay, both without and with the further addition of Fenton catalysts (Aseev and Batoeva 2014).

The formation of ·OH radicals in the course of HC processes, achieved by means of a circular Venturi tube, was independently proved in Japan by observing the acoustic energy and luminescence intensity (Soyama and Hoshino 2016). Comparison of numerical modeling and experimental observations of HC chemistry in water using a circular Venturi reactor and *p*-nitrophenol as a chemical dosimeter enabled researchers in Italy not only to further demonstrate the formation of hydroxyl radicals, but also to provide useful guidance for optimization and up-scaling (Capocelli et al. 2014). According to the latter study, the formation of ·OH radicals occurs despite a simulated bubble temperature (around 1300 K) significantly lower than reported elsewhere. All the Russian, Japanese, and Italian teams mentioned above worked with cavitation numbers above the supercavitation threshold ($0.1 < \sigma < 0.25$).

Wastewater remediation mechanisms

The main cleaning agent for wastewater remediation is the very large amount of energy released in the microenvironment surrounding the bubble upon collapse, which generates powerful oxidant hydroxyl radicals, capable of oxidizing toxic and non-biodegradable organic pollutants (Kumar and Pandit 2012; Pandit 2016). Accordingly, optimal oxidative degradation of organic pollutants requires well developed cavitation, characterized by a fairly large number of cavities undergoing strong enough collapse, namely cavitation numbers usually in the range $0.1 \leq \sigma \leq 1$ (Sawant et al. 2008).

Degradation of organics in wastewater, including hydrocarbons (Dindar 2016), to CO_2 and other simple products takes place at a fast pace, normally without generating harmful side products. The main effects of controlled hydrodynamic cavitation on contaminated water are (*i*) chemical oxidation of chemical and biochemical compounds, (*ii*) pyrolytic (thermolytic) decomposition, and (*iii*) mechanical disintegration, size reduction and solubilization of solid particles.

Thermolytic decomposition of volatile compounds takes place *inside* the vapor bubble where volatile compounds tend to migrate, whereas degradation of non-volatile and hydrophobic compounds that accumulate in the liquid phase occurs at the gas–liquid interface via oxidative reaction with the ·OH radicals mainly generated by cavitation processes, and *not* in the bulk liquid phase where the concentration of radicals is limited, as only 10% of the generated total radicals can diffuse in the bulk (the rest being recombined to H_2O_2 due to their short half-life) (Rajoriya et al. 2016).

The hydroxyl radicals, coupled to the above-mentioned extreme conditions of temperature and pressure, lead to advanced oxidation processes for the degradation and mineralization of organic non-biodegradable (recalcitrant) pollutants in wastewater, whose basic degradation mechanism is shown in eq. (8) (Rajoriya et al. 2016):

$$\text{(8)} \qquad \cdot\text{OH} + \text{organic molecule} \rightarrow CO_2 + H_2O + \text{some intermediates}$$

In general, to increase the amount of ·OH radicals in solution, aqueous hydrogen peroxide that readily dissociates into two ·OH radicals under cavitation conditions is conveniently added (Joshi and Gogate 2012). For example, in the removal of six of the most widely employed pharmaceuticals, which are also recalcitrant water micro-pollutants, optimal degradation (between 47% and 83%, depending on the molecule) required the addition of hydrogen peroxide in optimal 0.34 gL^{-1} concentration. Remarkably, higher concentrations were detrimental, as then hydrogen peroxide starts acting as a radical scavenger.

Hydrocavitation, furthermore, can be successfully coupled to Fenton chemistry, with the combined treatment strategy being more energy efficient and economical compared to individual application of HC and Fenton process (Bagal and Gogate 2014).

Besides the higher energy efficiency, hydrodynamic cavitation outperforms acoustic cavitation in cavitational yield, defined as the actual net production of desired products from the supplied electrical energy. This was again showed by Gogate and co-workers first using potassium iodide or *p*-nitrophenol as chemical dosimeters in a Weissler reaction affording yields up to one order of magnitude higher (Gogate et al. 2001) and then with several other reactions (Gogate and Pandit 2005).

Amongst hydrodynamic cavitation reactors, slit Venturi reactors outperform both circular Venturi and orifice plate ones in terms of cavitational yield (Patil et al. 2014; Maddikeri et al. 2014; Prajapat and Gogate 2015; Tao et al. 2016). Working on the reduction of the chemical oxygen demand (COD) of a real industrial effluent, a slit Venturi reactor achieved a cavitational yield 6 times higher than circular Venturi and 20 times higher than orifice plate (Rajoriya et al. 2016). Such results likely derive from the proportionality between the volume of the liquid vaporized (hence the bubble concentration) downstream of the orifice with the area or volume occupied by the shear layer (Gogate and Pandit 2011), along with the fact that slit sections have indeed a larger shear area, i.e., greater ratio of perimeter to cross sectional area than circular ones (Maddikeri et al. 2014).

Hydrodynamic cavitation of bacteria and microorganisms

Developed hydrodynamic cavitation, occurring at cavitation numbers above the supercavitation threshold, has been extensively studied in recent years as an innovative tool to inactivate microorganisms in wastewater, from bacteria to yeasts, spores, and even viruses (Dular et al. 2016). The main agent for the microorganism disinfection are the pronounced mechanical effects, i.e., generation of turbulence, jets, and shear stresses, causing the rupture of cellular walls, with chemicals (free radicals), and heat (local hot spots at the collapse of the cavitation bubbles) playing a supporting role only (Gogate 2007).

The combination of HC with other AOPs, such as the addition of hydrogen peroxide, ozonation, and ultraviolet treatment, possibly assisted by metal catalysts such as Fenton reagents, boosts the process lethality, allowing faster and more effective killing action by means of the loss of integrity of outer membranes (Gogate 2007; Loraine et al. 2012; Tao et al. 2016). Working on the combined cavitational–thermal inactivation of yeast strains (spores), we found that, among HC reactors, circular Venturi tubes far outperform orifice plates in terms of lethality, thereby confirming the results obtained with organic pollutants (Albanese et al. 2015). In the same study, an analytical model was developed and calibrated with experimental data, finding a double-peak lethality curve at low ($\sigma = 0.3$) and high ($\sigma = 1.2$) values of the cavitation number, as a consequence of mutually compensating effects of fewer bubbles with violent collapse at higher σ and more bubbles with milder collapse at lower σ.

As mentioned above, Dular and co-workers in Slovenia recently reported that rapid pressure decrease induced by supercavitation far outperforms all other explored physical treatments such as developed hydrodynamic cavitation, acoustic cavitation, and low pressure boiling in the eradication of bacteria from the strain *Legionella pneumophila* (Dular et al. 2016; Šarc et al. 2016). The physics underlying such results was described in terms of the very intense and rapid pressure drop at the transition from the liquid to vapor phase, occurring downstream of the cavitation nozzle in roughly 1 ms. Contrary to the sparse pressure shocks produced by developed cavitation, such sudden transition, widespread over the whole circulating liquid volume, leads to effective cell disruption and bacteria inactivation.

While further research over other bacterial strains is needed, this development leads to a very important consequence, namely the opportunity to exploit different cavitation regimes for wastewater remediation via properly tuned developed hydrodynamic cavitation for the treatment of organic pollutants and supercavitation for disinfection from certain types of microorganisms. This task is easily achieved either using different nozzles, or by adjusting the pump's operating point, or even by simply spanning a wide enough temperature range (exploiting the dependence of σ on the vapor pressure).

Treatment of real effluents

Several real world examples exist of HC applications for the remediation of industrial and urban effluents. In the following, four distinct cases are selected to show the versatility of the method (Aseev and Batoeva 2014), applied to real urban or industrial wastewaters, namely to multi-component solutions and not to over-simplified single-component solutions on the laboratory scale, as lamented by Tao and co-workers (Tao et al. 2016).

Wood finishing wastewater

In 2013, Pandit, Csoka, and co-workers studied the use of hydrodynamic cavitation to treat wastewater from the wood finishing industry, containing a high concentration of volatile organic compounds, using a cavitation reactor comprising a stator with indentations and rotor assembly (Badve et al. 2013).

The extent of COD reduction was found to depend on the speed of rotor, H_2O_2 concentration, and the residence time of wastewater in the cavitating device. Once again, addition of H_2O_2 resulted in enhanced degradation up to 5 g L^{-1} optimal concentration, beyond which it quickly decreased. Similarly, an increase in the residence time of the wastewater inside the cavitating device increases the degradation rate up to an optimum value, beyond which any further increase in the residence time decreases the degradation rate due to a reduction in the cavitational activity.

Sludge solubilization and disinfection

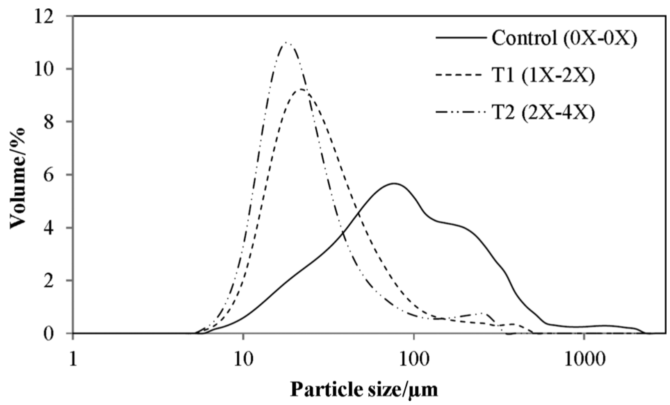
The controlled collapse regime of the cavitation bubbles generates extreme local shear forces, mechanical shock, and turbulence that disrupt solid agglomerates and lyse cells. Particles sizes are levelled, cells are destroyed, and so are flocculants and agglomerates, thereby achieving 20% to 30% improvement in methane gas yield in anaerobic biodigesters, along with a 15% to 25% reduction in digested sludge, as pretreated feed can be more easily digested by additional exposition (larger surfaces, longer residence time in suspension) of organic material to anaerobic bacteria.

For example, results obtained in the US to enhance biogas generation working with secondary sludge, showed that the sludge microparticles with broad size distribution centered at 150 μm are reduced to a mixture of microparticles much more narrowly centered at less than 22 μm following continuous flow cavitation, the greater the number of passages through the cavitation device, the more reduced and further narrowed the size distribution becomes (Fig. 3) (Gómez Barrantes 2013).

Similar results were obtained using the HC systems developed in India by HyCa Technologies to enhance biogas generation from anaerobic biodigesters by applying hydrodynamic disintegration, and again in the US in pilot tests by Arisdyne Systems (Reimers 2015) and in laboratory experiments by Dynaflow, the company founded in the late 1980s by Chahine (Dynaflow Inc 2016).

In both cases, the intracellular and extracellular components are set free and made available for biological degradation, which leads to an improvement in the subsequent anaerobic process, aiding the digestion process in turn eventually leading to increased biogas production. The graph in Fig. 4 shows the lower

Fig. 3. Particle size distribution of secondary sludge sample from municipal wastewater treatment plant before and after controlled cavitation under flow. [Reproduced from (Gómez Barrantes 2013), with kind permission].



operational costs that a company should bear when adopting HC in place of mainstream sludge secondary treatment technologies.

In a comprehensive investigation carried out over waste-activated sludge produced by a municipal wastewater treatment facility in Poland, Grübel and Suschka set up an installation capable of treating 500 L/h, including an alkalization section (with NaOH, up to pH ≈ 9), a circular Venturi-type cavitational reactor operating in developed cavitation regime (σ = 0.245), and a few biodigesters (Grübel and Suschka 2015). Among their most relevant findings concerning the synergistic alkalization + cavitation processes, biogas production increased by 22%–27% over ordinary biodigestion, organic matter solubilization increased on average by 35% over the values obtained after separately applying alkalization or cavitation, organic matter after biodigestion decreased by 50%, while the overall process showed greatly attractive also due to its low chemical and energy intensity (13%–28% higher biogas yield).

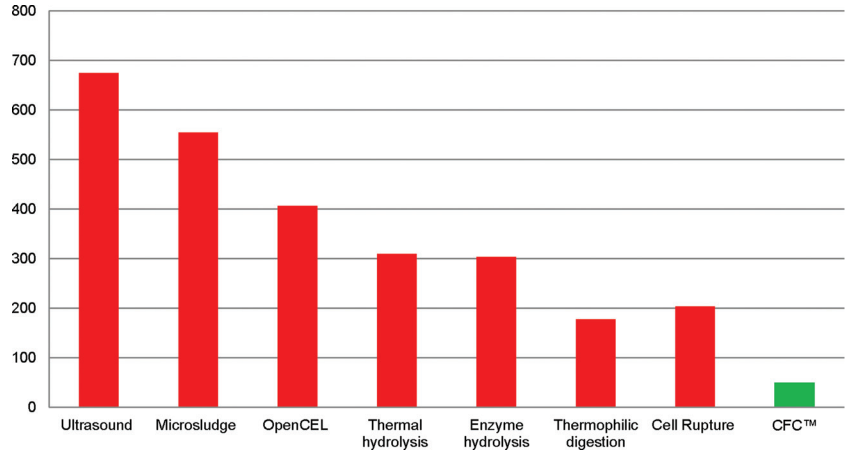
Moreover, the microbiological safety of the digested sludge was significantly enhanced with respect to the most relevant pathogen microorganisms, such as *Salmonella*, sulphite-reducing *Clostridia*, *Escherichia coli*, and *somatic coliphages*, the latter representative of human enteroviruses due to their very similar structure and, likely, vulnerability to the same inactivating mechanisms. The main general mechanism for both sludge solubilization and microorganisms' inactivation, indeed, was identified in cell walls weakening by alkalization, which made them more susceptible to lysing and oxidation processes produced by hydrocavitation (Grübel and Suschka 2015). Finally, another important advantage, is the production of microbiologically safe digested sludge ready to be used for agricultural applications.

Sewage disinfection

Jyoti and Pandit reported as early as 2003 that disinfection of water with hydrodynamic cavitation coupled with hydrogen peroxide is an economically attractive alternative, compared to techniques such as chlorination and ozonation, in the technical task of limiting to below the maximum acceptable threshold the counts of *Total coliforms*, *Fecal coliforms,* and *Fecal streptococci* bacteria frequently present in water, where they may originate a number of serious waterborne diseases (Jyoti and Pandit 2003).

Promising results were obtained about 10 years later also by Chahine and co-workers using the above-mentioned cavitating jet technologies to disinfect gram-negative bacteria including *Escherichia coli*, and gram-positive *Bacillus subtilis* (Loraine et al. 2012). Within 60 min in a 2 L batch reactor magnitude using a proprietary nozzle operated at 2.0 bar pressure (corresponding to CN = 0.5) generated by a 3.7 kW pump, the concentration of *E. coli* was reduced by five orders. The team could confirm that the killing

Fig. 4. Electricity consumption (units: kWh/ton) for different sludge treatment technologies employed in advanced anaerobic digestion plants. CFC, a trademark of Arisdyne Systems, stands for controlled flow cavitation. [Reproduced from (Reimers 2015), with kind permission]. [Colour online.]



mechanism was cell's wall rupture, with the gram-negative species with thinner cell walls being degraded by HC much more rapidly and extensively than thick walled *B. subtilis*.

Dular and co-workers lately showed that different hydrodynamic cavitation removal mechanisms are required for successful degradation of different pollutants, including cyanobacteria, green microalgae, bacteria, and viruses, from water and wastewater. Rotavirus concentration were reduced by as much as 75% after a single cavitation treatment of the sample. Promising results were achieved with *Legionella pneumophila* (full bacteria removal requiring a shear-induced supercavitation reactor rather than the Venturi design), and mixed results with cyanobacteria and microalgae: fairly high inhibition for toxic strain of cyanobacteria *M. aeruginosa,* but poor removal of a strain of green microalgae *Chlorella vulgaris* (Dular et al. 2016).

The different behavior of the latter two microorganisms after exposure to hydrodynamic cavitation was ascribed to the absence of cell lysis in both of them, while cyanobacteria cells suffered from the collapse of gas vacuoles that are missing in the cells of *Chlorella vulgaris*. A combination of HC with other treatment methods like ultraviolet irradiation, non-cavitation ultrasound or chemicals, as well as to a more effective design of cavitation chambers to obtain higher pressure differences, was suggested for the removal of microalgae.

A successful cavitator developed for the treatment of sewage with the aim to test and evaluate long-term operations has been successfully installed in western Hungary (Csoka 2015). Since June 2015, the rotor-stator type cavitator displayed in Fig. 5 was operated round the clock (24 h, 7 days), treating 4000 L/h (15% of the overall wastewater flow), while powered by a variable power (4.5 to 11 kW) electric pump, with the higher power required to increase the capacity to 10–12 m^3/h in future tests.

During one year, the team did not observe any failures, while saving as much as 40% of the hydrogen peroxide normally added to aid water disinfection. The customer has claimed its full satisfaction, bacterial infection ended, and work is in progress to scale up the cavitator, while another HC equipment has been installed at the facilities of a different company.

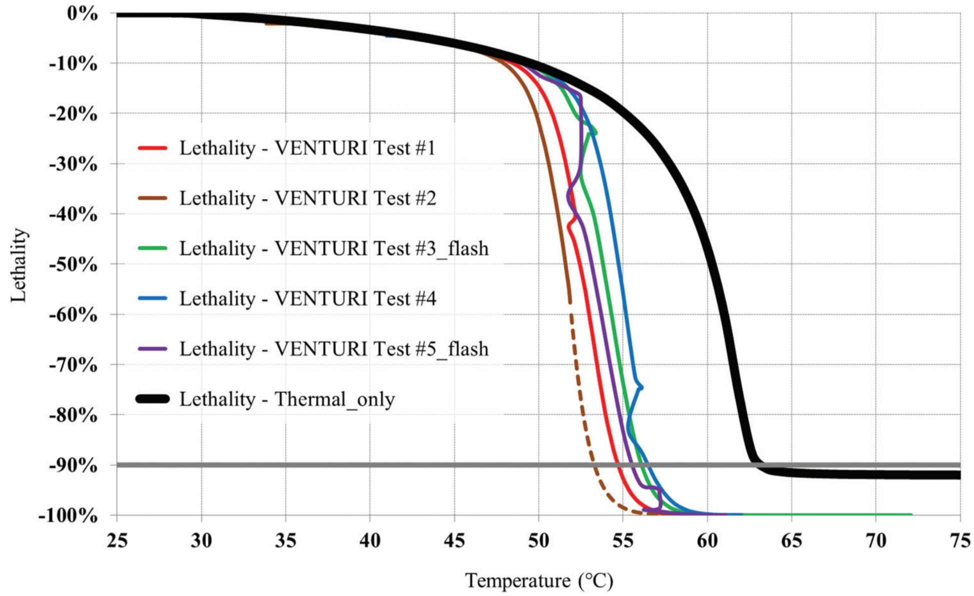
Fig. 5. A section of the rotor–stator type cavitator device installed in June 2015 in western Hungary at a wastewater treatment plant to test long term. [Photo courtesy of Prof. L. Csoka, Western Hungary University]. [Colour online.]

Brewing water disinfection

A major application of HC is the energy efficient inactivation of *Saccharomyces cerevisiae*, namely the yeast strain used across the world for beer brewing, as well as a spoiling agent for milk and juices, lately carried out in Italy using different reactors to demonstrate the process feasibility on the industrial scale (Albanese et al. 2015). While the scope of that research addressed liquid food pasteurization, the results are of relevance for the treatment of wastewaters contaminated by yeast strains and spores.

In full agreement with results from the HC-induced degradation of recalcitrant chemical pollutants in aqueous solutions coupled to Fenton chemistry (Pradhan and Gogate 2010), the team showed that the circular Venturi tube configuration performed significantly better that the orifice plate in terms of lethality rate.

Fig. 6. Yeast lethality curves for all VENTURI tests; the dashed portion of the brown curve highlights the extrapolation beyond the maximum temperature achieved in the VENTURI test #2; the thick black curve represents the yeast lethality simulated in the absence of any cavitation process. [Reproduced from (Albanese et al. 2015), with kind permission]. [Colour online.]



Noticeably, the geometry of the used cavitation reactor agreed with later stringent recommendations (Šarc et al. 2017).

The team's model simulating the combined thermal and cavitational effects on yeast lethality nicely accommodates the experimental data (Fig. 6) into a comprehensive framework pointing to a hybrid and strong synergistic "thermal + cavitational" effect, thereby providing a tool to design an optimal (industrial) cavitation reactor by predicting results when changing the process parameters. In detail, 90% yeast strains lethality was observed at 6.3–9.5 °C lower temperature, resulting in about 20% lower energy consumption. Energy savings well beyond 20% are feasible by inserting more cavitation reactors in series along the main circuit to increase the frequency of occurrence of cavitation processes, as well as by further optimizing the cavitation regimes by exploring higher σ regimes (i.e., after increasing the hydraulic pressure), as the model predicts a peak of the cavitational yield beyond the range of the explored values for σ.

Outlook and conclusions

Easily scalable hydrodynamic cavitation operated in continuous mode is emerging as an energy efficient and cost effective water cleaning technology with several advantages over conventional chemical and biological treatment processes. In a rather rare case in the history of science, the scientists who pioneered the study of the discipline, mostly Pandit, Gogate, Kozyuk, and Chahine, advanced both the hydrodynamic cavitation science and its engineering (the technology).

For about two decades, progress in hydrodynamic cavitation for environmental remediation was apparently shared across a limited scientific community. For instance, in one of the first books on the applications of hydrodynamic cavitation to environmental remediation, Ozonek in 2012 noted that the use of HC to eliminate pollutants from water had not been fully researched, with most research having focused on cavitational erosion of equipment, namely the negative aspects of cavitation (Ozonek 2012). Four years later, Dular and co-workers emphasized that "the limited use of HC compared to less energy efficient and less versatile acoustic cavitation" was the outcome of "poor communication amongst scientific fields" (Dular et al. 2016).

The pioneer researchers mentioned above, however, established the cavitation regimes useful for wastewater remediation, including supercavitation, built the first successful HC reactors suitable for practical application, and established new companies, which are now applying controlled HC to a variety of industrial sectors including hydromechanics, mixing, homogenization, dispersion, nanomaterials, synthesis, and biotechnology.

Applications to wastewater treatment, we argue in conclusion, will now rapidly expand as the technology offers the possibility to simply retrofit existing plants, while the capital and operational expenses are comparatively low. A company based in Singapore, for example, uses a patented HC technology named Dpasys by means of which it has treated some 1.5 billion liters of municipal wastewater, managed an innovative fingerlings hatchery, as well as cleaned the water of swimming pools in a luxury real estate by means of energy-neutral cavitation reactors, which were simply installed along the conventional swimming pool recirculation piping (DPA system 2016).

We forecast that within the next 10 years, many of the new effluent treatment plants built in China between 2000 and 2014 (when the total number of wastewater treatment plants in China increased from 481 to 3717, to currently process some 140 million cubic meters per day) will be retrofitted with hydrocavitation reactors to effectively treat and mineralize new bio-refractory molecules (pesticides, dyes, inks, synthons, and pharmaceutical drugs) that are continuously being released into the environment, as well as to inactivate harmful microorganisms and viruses, especially since today research on HC for wastewater treatment in China is well established and rapidly growing (Tao et al. 2016). About two-thirds of existing treatment plants in China, indeed, still use traditional extended aeration, consuming 50% more power than anaerobic sludge digestion, with the Government calling for "technological breakthroughs" (Workman 2015).

In general, as discussed in the previous sections, the geometry of the HC device (Venturi-tube reactors, especially slit ones, being the preferred choice), the operating pressure and cavitation number, the right dosage of H_2O_2 and possibly of mineral catalysts such as Fenton reagents or alkalization substances such as NaOH, are the key design parameters that decide the efficacy of HC in degrading refractory biological and chemical pollutants on large scale. Finally, the ongoing renewable energy boom (Meneguzzo et al. 2015), quickly lowering the cost of electricity across the world, will only accelerate the adoption of hydrodynamic cavitation, powered only by electricity, as an eminent technology of our common path to sustainability, with energy and clean water access for all.

Acknowledgements

This article is dedicated to Professor A.B. Pandit, Institute of Chemical Technology, Mumbai, for all he has done to advance hydrodynamic cavitation from a laboratory curiosity to a multipurpose, eco-friendly technology that will benefit mankind for decades to come. Thanks to Professor Levente Csoka, University of West Hungary, for helpful discussions dating back to SuNEC 2015.

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