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Water disinfection using acoustic cavitation: A mini review

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Abstract

The waterborne disease is a major concern for India and root cause of this non-ability of water disinfection technology at affordable cost to all. Hence it is necessary to understand the disinfection of water to achieve goal of healthy society. Various methods and technologies like Chlorination, iodine, silver, coagulation flocculation, iron Nano particles, UV, Solar disinfection, distillation, Reverse osmosis, slow sand filters, activated charcoal filter, electrochemical oxidation, cavitation, plasma techniques, electrocoagulation, photo catalysis and many more have been evolved over the years. Despite of availability of techniques for water disinfection, but larger scale application still is a major challenge, especially in developing countries where almost eighty percent diseases are cause by waterborne. Acoustic cavitation is base technique highly useful for water disinfection. This mini review discussed various aspects of acoustic cavitation and potential application for water disinfection. Acoustic cavitation with chemical disinfection techniques is also very beneficial because it reduces the use of chemical so production of byproducts reduces automatically.

*Keywords:*Disinfection, Cavitation, Acoustic Cavitation, waterborne diseases.

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1. Introduction

Water is integral component of millions of living bodies, daily need of humans and other species. Purity of water is major concern for the human society to achieve the healthy society and sustainability goals. Over the years of scientific and technological advancement has developed various physical, chemical, and biological techniques to purify the water. Commonly practice techniques for water disinfection are gravity settling, coagulation, filtration, and chemical processes like chlorination and ozonation. Chlorination is most commonly and widely used process for water disinfection. Chlorine has mutagenic effects on human body, may leads to cancer and other problems with chlorination are odour and taste. Alternative for chlorine are ozone, silver, copper, ferrate, iodine, bromine, hydrogen peroxide, potassium permanganate. These chemicals are useful for water disinfection with some associated advantages and disadvantages. Physio-chemical systems, such as photo-catalysis, photodynamic, electrochemical and some physical systems, ultraviolet irradiation, pulsed electric fields magnetic and microwave systems are also use for disinfection (Carpenter et al., 2017). For disinfection of water and wastewater we need such phenomenon were risk of associated phenomenon should be very low. Cavitation and other advanced oxidation processes are evolving with minimum associated risk compare to chemical processes.

2. Cavitation

2.1 Basics of Cavitation

Cavitation is a process of formation and collapse number of cavities at million locations in reactor/system. Bubbles formed during cavitation attains very high temperature and pressure (inside bubble) and release of very high energy in extremely small location. Generation of high temperature spots, highly active radicals and turbulence makes cavitation a very efficient and effective method for water disinfection (Gogate, 2007). Cavities can be generated by various methods like acoustic cavitation, hydrodynamic cavitation, optic and particle cavitation. Out of these methods hydrodynamic and acoustic cavitation is well-established techniques at laboratory and pilot scale. Temperature, static pressure, fluid flow dynamics, velocity of fluid is important parameters which affect the formation of cavitating conditions. Temperature can be reached up to 4500 °C and pressure is about 10000 atm. During the collapsing of cavities it leads to formation of high oxidizing power chemical species $HO^{\bullet}$, HO_2-, which have potential to remove organic pollutant from water. Cavitation have nowadays use in various fields like in producing emulsion solution, for making highly efficient heating devices, different types of surfaces cleaning, it is very useful in pumping of highly viscous fluid, effluent treatment, organic contaminant treatment, cosmetic treatment etc. Chemical synthesis, cell disruption in biotechnology, sono-crystallization. Atomization (process of formation of small droplets) obtained by cavitation technology. This mini review addressed the concerns of water and water disinfection aspects of cavitation using acoustic and hydrodynamic cavitation and associated microbial aspects.

2.2 Types of cavitation & Cavitational Reactors;

Cavitation is classified base on formation of the cavitation bubbles and following four ways are useful for understanding.

1.Hydrodynamic cavitation
2.Vaporous cavitation
3.Gaseous cavitation
4.Acoustic cavitation

Gogate et al (2006) classified cavitation in four types such as hydrodynamic cavitation, acoustic cavitation, optic cavitation and fourth particle cavitation. Optic cavitation generated by very high intensity of photon particles (laser beam)(Gogate et al., 2001; Gogate & Pandit, 2000) rapturing it in liquid medium, particle cavitation is generated by elementary particles (neutron) beam rapturing a liquid. Two types of cavitational reactors are most common in use first sonochemical reactors and another is hydrodynamic cavitational reactor. Important configurations of sonochemical reactors are given below-

1.Ultrasonic horn and bath
2.Dual frequency flow cell
3.Triple frequency fuel cell
4.Ultrasonic bath with longitudinal vibrations

Ultrasound can be generated by various gas and liquid driven transducers, electromechanical transducers like magnetostrictive and piezoelectric. Ultrasonic bath, probe and the ultrasonic flow cell are commonly used sonication equipment (L. Zhang et al., 2017).

Gogate and Kabaddi (2009) describes details of hydrodynamic cavitation, according to them hydrodynamic cavitation generated by the high RPM of any object in liquid medium. Hydrodynamic devices such as high-speed homogenizer, high-pressure homogenizer, and speed rotor are able to generate cavitational conditions but due high energy, cost investment for these reactors make it non-feasible for the water treatment purposes. Comparing the intensity of collapsing of cavity hydrodynamic cavitation produce less intensity but in term of the cavity generation hydrodynamic cavitation have advantage because of its geometrical configurations(Destaillats et al., 2001).

Mahulkar and Pandit (2010) described two possible way of cavity collapsing one is symmetrical collapsing and another is asymmetrical collapsing. Symmetrical collapsing stated for those collapsing in which bubble maintain spherical or distorted spherical shape till the point of collapse, production of free radicals and thermal pyrolysis occurs in efficiently. Further collapsing of the bubble takes place in a symmetrical or asymmetrical way and depends upon the nearby cavities(Save et al., 1997). Collapsing cavity generate extremely intense shock waves. Asymmetrical collapsing is favorable for microbes killing and symmetrical collapsing is favorable for production of high oxidation potential radicals such $HO^{\bullet}$, HO2- and H2O2 due to decomposition of water molecules (Gogate et al., 2006). Shock wave generated due to collapsing of cavity cause shock wave of 550MPa at speed of approximately 2000m/s and water jets (micro water jets from during asymmetrical collapsing) generate a kind water hammer effect of 450MPa at 100m/s. Thermal effect is plays very important role, at collapsing cavity hot spot of 2000K-5000K is generated its persuades the heat transfer of 1010K/s. Thermal, chemical and physical effects provide killing of water microbes and degradation of water pollutant (Ferrari, 2017).

Cavitation is classified in 4 category and these categories are depends upon the way cavity is generated, hydrodynamic cavitation, acoustic cavitation, optic cavitation, and particle cavitation. Out of four cavitation hydrodynamic cavitation and acoustic cavitation is more suitable for water and wastewater treatment. Hydrodynamic cavitation is more energy efficient and more scope of developing at commercial scale for water and wastewater treatment.

3. Acoustic Cavitation

Ultrasound has many applications, but one of the most important is cell disruption of bacteria, viruses, animal cells fungal cell etc. It is proved that limited quantity of bacteria cells can be disintegrated very efficiently using ultrasound. Transient and stable acoustic cavitation are two forms of ultrasonic cavitation violent collapsing of bubbles occurs in transient way and microstreaming occurs in stable cavitation.

3.1 Factors affecting the Acoustic cavitation:

Frequency and intensity of sound wave is most important of acoustic cavitation and other parameters are liquid medium properties such as viscosity and surface tension. Increase in frequency leads to decrease in cavitation due to very small rarefaction period (Gągol et al., 2018; Yadav et al., 2020). Increasing the viscosity of medium up to optimum level increase the cavitation. Temperature, presence of dissolved gases helps to increase the cavitation. Increasing the sound wave intensity provides more cavitation and these are useful parameters cell disruption studies of bacteria. Increase in size of microbial cell decrease the cell rapturing because bigger cell can withstand larger tensile stress (Li et al., 2014).

3.2 Mechanism of microbial inactivation:

Conclusive mechanism for cell disruption is still not established but following key points plays role in cell disruption.

3.2.1Mechanical Effects:Doulah and Hammond (1975) proposed the eddies formation by sound waves results to the pressure difference across the cell wall of microbes and if pressure difference sufficient enough and cross cell wall strength disintegration of microbes occurs(Mahvi, 2009).

3.2.2 Shear Stress:localized shear stress developed during the transient cavitation due to formation of shock waves, these shock waves produce sufficient shear stress and turbulence to rapture the cell wall.

3.2.3 Free Radical Formation and Dis-agglomeration: Sonntag (1996) observed that not only physical forces but free radical generation because of cavitation are also responsible for the microbes killing (Moholkar & Pandit, 2001).

articles in professional journals, which publishes papers for specialists and do not ordinarily pay for contributions, may benefit a person in many ways. Such publications are likely to increase career advancement, to increase your circle of your professional acquaintances, to get feedback of your ideas, etc. Usually, papers submitted to the journals are very large and many a times they are either rejected or returned with a request for major/ minor revisions. A paper is turned down for a number of reasons, which is not only due to the quality of work but also due to the quality of presentation. Although quality of work and presentation are equally important.

4. Acoustic Cavitation as Water Disinfection

Microbial cell destruction using ultrasound waves are started early in 1920s by work of Loomis and Harvey. Scherba et al. examine various fungus, bacteria and viruses on ultrasound of 26kHz and find that at high intensity and high exposure time bacteria killing occurs (Vajnhandl et al., 2015). Mason et al. used martin Walter push and pull reactor at 27 kHz for water disinfection, after 60 min of sonication approximately 73% of viable bacteria destroyed. Similar unit of ultrasonic used for cooling tower water treatment at flow rate of 10 l/min and sonication unit was of 300W for 120 hours, 85% of viable bacteria deactivated (Mason et al., 2003). Jyoti and Pandit used bore well water for bacterial deactivation analysis using ultrasonic alone and combinations with ozone(Jyoti & Pandit, 2004). Researcher studied microbial deactivation analysis on four bacteria/group of bacteria and find almost 99% removal using ultrasonic bath and ozone (0.5mg/l).Almost same results obtained for ultrasonic horn and ozone combination, using alone ultrasonic horn and ultrasonic bath achieved 50% to 57% percentage disinfection (Jyoti & Pandit, 2004). This studied proves that use of chemical disinfectant can be reduce by assisting disinfection process with ultra-sonication. Dadijour et al. studied ultra-sonication with TiO2 and called it sonocatalytic disinfection(Dadjour et al., 2005) on E.coli. Culture were studied in absence of TiO2 and also in presence, 2% reduction found in 30 min period using only ultrasonic, with 1.0 g/ml concentration of TiO2 with ultrasonic achieved 13% bacterial reduction which indicated significant growth in bacterial reduction. Tsukamoto et el. 2003 investigated inactivation of yeast cells at 27.5mHz, researcher consider yeast cells similar to Cryptosporidium parvum which is very resistant to germicides because of hard oocysts(Tsukamoto et al., 2004). Using horn type sonicator at 27.5 MHz at 33 ml/min flow rate up to 97% inactivation achieved while at higher flow of 1500 ml/min inactivation decreases to 79%. This study indicates that water disinfection can be achieved even if water includes Cryptosporidium parvum like persistent microorganism.

Futura et al. 2004 studied water disinfection using horn type sonicator (27.5 kHz) utilizing the squeeze-film effect and measured the formation of hydrogen peroxide during irradiation by using KI colorimetric method. Using this squeeze-film type system, more than 99% of E. coli cells was inactivated within 180-s sonication at the amplitude of 3 lm (p–p) and 2 mm of the thickness of the squeeze film. Study also confirmed that more than 99% of the Saccharomyces cerevisiae cells were inactivated after 40 seconds of Ultrasonic irradiation at 7 µm (p–p) and 2 mm of the thickness of the squeeze film and almost 80% of the Cryptosporidium parvum oocytes were morphologically damaged after 300-s treatment at the amplitude of 4 µm (Furuta et al., 2004).

Zhang et al. studied the removal of Microcystis aeruginosa using ultrasound for 5 minutes at 50W decrease significantly color of algae solution(Zhang et al., 2006). K. Iqbal et al. studied the effect of high-intensity focused ultrasound (HIFU) on Enterococcus faecalis on both planktonic suspensions and biofilms and concluded that HIFU causes bactericidal effects. Ortuno (2014) studies inactivation kinetics of Escherichia coli (E. coli) and Saccharomyces cerevisiae (S. cerevisiae) cells in apple juice subjected to supercritical carbon dioxide (SC-CO_2) assisted by high power ultrasound (HPU) at different pressures (100-350 bar, 36 ºC) and temperatures (31-41 ºC, 225 bar) and concluded that shorter process time required to achieve total inactivation. There was a direct relationship observed between cellular modification/damage and inactivation provoked by the SC-CO_2 and SC-CO_2+HPU treatments on E. coli and S. cerevisiae cells(Ortuño et al., 2014).

Gao et al. 2014 used high frequency ultrasound 850kHz to kill Enterobacter aerogenes, Bacillus subtilis and Staphylococcus epidermidis as well as a yeast in controlled temperature, 99% inactivation of bacteria achieved. ultrasound generator K80 (Meinhardt Ultraschalltechnik, Germany) at 850 kHz, which was connected to an ultrasonic transducer E/805/T and a double-walled cylindrical glass vessel. Researcher concluded that the longer the residence time of the bacteria in the ultrasonicated medium, that is after sonication treatment is stopped, the higher the number of inactivated bacteria cells(Gao et al., 2014).Ultrasonic Resonator was developed Osman et al. for the Ballast water disinfection named it as multiple-orifice resonators (MOR)(Osman et al., 2016), researcher demonstrated that use of multiple orifice plates increases the ultrasonic irradiation surface two times without any increase in mass of device. MOR resonators can potentially increase efficiency of disinfection. Using Bacteriophages MS2 (E. coli (ATTC 15597-B1)) and ΦX174 (Host bacterium is E.coli (ATCC 13706)) obtained 0.123 per minute inactivation rate at 582 kHz + visible light combination For MS2 (initial concentration is 11,133 pfu/ml). Using combination of ultrasonic (582 kHz) and visible light bacteria phase ΦX174 (initial concentration 6388 pfu/ml) received inactivation rate of 0.042 per minute, researcher concluded that MS2 inactivation is faster comparing to ΦX174 and the combined use of US and VL should be employed only on specific cases(Chrysikopoulos et al., 2013). Antoniadis et al. examined the sonication of municipal wastewater and observed that high power(Antoniadis et al., 2007) and low frequency combination is eliminating complete E.coli. Onder et al. studied combination of ultrasound, chlorine dioxide and provided that using sequential combination is more promising comparing to using alone(Ayyildiz et al., 2011).

Table 1. Water Disinfection Using Acoustic Cavitation

Sr.no	**Microbes and pathogens**	**Acoustic device & various Parameters**	**Reduction (%)**	**Reference**
1	B. subtilis	Martin Walter push–pull system 27kHz push–pull reactor in a glass vessel of volume 5 l, 20 l, 60min, Flow rate of 101/min. 300 W	70% in 1 hour	(Mason T.J. et. al.)
2	HPC bacteria, Total coliforms, Fecal coliforms, Fecal streptococci	Ultrasonic horn (Supersonics), Ultrasonic bath frequency of 22 kHz, power rating of 240W, ultra sonication for a period of 15 min temperature 35–37 ◦C internal dimensions- 145mm×145mm×150 mm	US-horn US-bath bacteria 50 57 HPC 55 75 Total coli. 47 89 Fecal. Coli 50 80 Fecal strep.	(K.K. Jyoti, A.B. Pandit)
3	Escherichia coli	Ultrasonic sonicating bath (UT 204; Sharp Co. Ltd., Tokyo, Japan) TiO2 pellets 39 KHz, 200W temperature - 20 ◦C, Irradiation was performed in the dark,Time 30min.	2% only TiO_2 13% when TiO_2 used with ultrasonic irradiation,	(D.F. Mahmoud et, al.)
4	Saccharomyces cerevisiae (yeast cells) Cryptosporidium parvum	27.5 kHz horn-type sonicator, 26.6 kHz squeeze-film-type sonicator, ultrasonic irradiation was 42 WmL^{-1} temp.- 34 ^{0}C,	Flow rate Inactivation% 33 97 240 89 1500 79	(I. Tsukamoto et, al.)
5	Escherichia coli XL1-Blue	Horn type sonicator (27.5 kHz) utilizing the squeeze-film effect. Maximum power of sonicator by ultrasonic irradiation was 42 Wml^{-1} at amplitude vibration face of 7µ at Room temp	99% within 180 second at the amplitude of 3 lm (p–p) and 2 mm of the thickness of the squeeze film,	(Furuta, M et, al.)

Table 2 (Cont'd). Water Disinfection Using Acoustic Cavitation

Sr.no	Microbes and pathogens	Acoustic device & various Parameters	Reduction (%)	Reference
6	Microcystis aeruginosa	20 and 80 kHz ultrasound waves, generates 150, 410, 690, 1320 kHz ultrasound waves. Working volume of the cell system- 1000 mL Surface area-15.3 cm2. Temperature controlled at 25 ± 3 ^{0}C,	Chlorophyll a concentration change to 0.26mg/l after 20 minutes sonication, 80 kHz, 80 W	(Z, Guangming et, al.)
7	Enterococcus faecalis	High-intensity focused ultrasound (HIFU), bowl-shaped, 64-mm–diameter piezo-ceramic transducer, resonance frequency of 250 kHz, water tank with dimensions of 15×15×25 cm^3 HIFU source transducer- geometrical focus and focal depth of the transducer were 59.97 mm and 50.65 mm, The strongest ultrasonic pressure (~10 bar) is measured at the focus	No viable cells were detected after 60 or 120 s of exposure to HIFU in planktonic suspensions,	(Kulsum et al.)
8	Escherichia coli (E. coli) and Saccharomyces cerevisiae (S. cerevisiae) cells	High power ultrasound (HPU) different pressures (100-350 bar, 36 ºC) temperatures (31-41 ºC, 225 bar) Power generator unit (40 W ± 5 W). resonance frequency of 30 kHz	**E. coli cells**-After the first minute, the population decreased slowly and on average, a reduction of 7.5 log-cycles was obtained after 7min **S. cerevisiae**- The population reductions obtained after 1 min of treatment were 1.8, 3.9 and 4.8 log-cycles, at 31, 36 and 41 ºC, respectively.	(Carmen Ortuno, et. al.)
9	E. aerogenes, B. subtilis, S. epidermidis, and A. pullulans	Ultrasound generator K80 (Meinhardt Ultra schalltechnik, Germany) at 850 kHz, Ultrasonic transducer E/805/T Glass vessel was filled with 250 ml Milli-Q water. 5 ml microbial suspensions were transferred into a 15ml glass tube Working temperature in the vessel 20 ^{0}C.	~4.2,~2.5 and ~4.4 log reductions achieved at 62 W for 20 min Ultrasonication for E. aerogenes, B. subtilis and S. epidermidis, respectively, in stationary phase.	(Shengpu Gao et al.)
10	Bacteriophages MS2(E. coli (ATTC 15597-B1)) and ΦX174 (Host bacterium is E.coli (ATCC 13706))	(Meinhardt Ultra- schalltechnik, with 75mm titanium transducer, function generator and amplifier. 2L glass reactor, operating Frequency 582, 862, and 1142 kHz Visible light combined US + VL	MS2 inactivation faster than ΦX174, **ΦX174** - At C_0 of 6388pfu/ml and 582 kHz inactivation coefficient is 0.042 1/m, **MS2** – At C of 11133 pfu/ml at 582 kHz inactivation coefficient is 0.123 1/m,	(Chrysikopoulos et al.)

Table 3 (Cont'd). Water Disinfection Using Acoustic Cavitation

Sr.no	Microbes and pathogens	Acoustic device & various Parameters	Reduction (%)	Reference
11	E.coli.	1- Ultrason 250 (LabPlant, UK) ultrasound generator, 80kHz, 150W, horn of 7mm tip 2- 24 kHz, a UP 400S (Dr Hielscher GmbH, Germany) horn-type sonicator, 100ml sample used for irradiation.	Microbial loading reduced to 5000 col/ml from 10^6 col/ml	(Antoniadis et al.)
12	E.coli., Total Coliform	Ultrasonic generator (Vibra Cell505, 500W and 20 kHz, metallic probe of 1.9cm dia.	For the power range of 75–300 W/L, doubling ultrasonic power enhanced E. coli and TC log inactivation by a factor of 1.7–2.8	(Onder et al)

Various researchers find acoustic cavitation a very efficient tool for water disinfection; acoustic cavitation becomes more useful when used with other chemical disinfectant. At the lab scale acoustic cavitation is very effective but for the larger scale of water disinfection it's still challenging task for the researchers. For every technologies cost is one of the most important factor, many technologies available efficiently but there actual application with economical cost is still bigger challenge than research itself. Cost of ultrasonic horn used alone for water disinfection is much higher than using ozone/hydrogen peroxide for same degree of disinfection. Nevertheless, cost get reduce when ultrasonic horn used with ozone, but it is still higher than using ozone alone for same disinfection. Compare to ultrasonic horn ultrasonic bath have comparatively less cost per liter for achieving same disinfection(Kishen Kumar & Pandit, 2012). Using acoustic cavitation with chemical disinfectant reduces the amount the chemical requires which also leads to the reduction in harmful by products formation.

5. Conclusions

Cavitation is emerging water disinfection technology and since last decade research is continuing cavitation base technologies. Nowadays, researches on more focused on effect of acoustic cavitation on E.coli. Extensive research done on water disinfection using acoustic cavitation but making acoustic cavitation feasible for large scale and economical for domestic scale. Several water treatment units based on cavitation patented overs last few years like DYNAJETS, VRTX, HyCa, Vorsana Radial Counter flow reactor etc. Future contains promising believe in cavitational technology for water treatment. Combining acoustic cavitation and hydrodynamic cavitation with other technologies are now bigger field of research.

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