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Water treatment using ultrasonic assistance: A review

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Abstract
One of innovate techniques that was used for improvement of water treatment process is application of ultrasound waves. In this study, different applications of ultrasound technology in water treatment process such as membrane filtration, turbidity and total suspended solid reduction, algae removal, disinfection process, water softening process and other pollutants removal such as halomethanes and DDT were surveyed. The results show this technique could improve the water treatment process environmentally. The various parameters could affect to the efficiency of ultrasound technique such as power density, frequency and irradiation time. So it is needed to obtain the optimum power density, frequency and irradiation time to reach cost-effective. The most experiments are carried out in laboratory scale due to its cost. The utilization of solar energy may help to decrease the cost. It is suggested that the ultrasound technique could be extended to clean up of other polluted parameters in water and the environment.

Keywords pollutant parameters; water treatment; ultrasound; cost.

1 Introduction

It is clear that water is one of the essential substances for living system and it is necessary for human survival on the earth (Tansel, 2008; Ambashta and Sillanpaa, 2010). All humans daily consume water to sustain life and maintain a good health, therefore water conservation is important and its quality must meet specific standards. The quality of water is determined by many factors such as physical, chemical or biological parameters. The main sources of drinking water are lakes, reservoirs, canal, ground water, sea water, rain water, atmospheric water generation and fog collection that depending on the source of pollutant, their pollution could be different (Ferguson et al., 2009; Huang et al., 2008; Zhang et al., 2009; Ackah et al., 2011; Sayyed and Wagh, 2011; Tiwari, 2011; Zhang et al., 2011). All water in earth is not good for drinking purpose and must use of some treatment process to achieve the standard quality for therefore we are facing a challenge to produce suitable drinking water. General treatment of drinking water is consisting of several stage to remove or reduction of suspended, dissolved solid and microbial pollutants.

Main process of water treatment include flocculation, sedimentation and media filtration to remove colloidal and suspended solids, ion exchange, carbon adsorption and membrane processes to remove dissolved solids; and at last stage a disinfection for microbial inactivation that often performed by chlorination, ozonation and ultraviolet radiation(UV) (Tansel, 2008). Any process of drinking water has some purification limitation and application problems such as high cost, ineffective for removal some pollutant, operation problems and generate toxic secondary pollutants (Gaya and Abdullah, 2008). For example, common problem in membrane filtration is fouling and in disinfection with chlorine product DBP_s (disinfection by products) is a serious problem (Liu et al, 2005). Many investigations have been performing to eliminate this limitation by application of innovates technique such as semiconductor catalysts, forward osmoses, advances oxidation process and magnetic purification (Chong et al., 2010; Ambashta and Sillanpaa, 2010). One of the innovate technologies that was used for improvement of water treatment process is application of ultrasound (US) waves having a frequency of 20,000 Hz or above that is called “sonication”.

1.1 Ultrasound

Ultrasound is longitudinal wave with a frequency above 20 kHz (Leighton, 1994). This frequency is above the sonic range (20 Hz to 20 kHz) at which humans can hear and below the mega-sonic region (>600 kHz) (Deymier et al., 2004; Wong, 2002). In US waves, energy is transmitted by the vibration of the molecules in the environment where the wave is being spread (Bello et al., 2005). US could generate by two techniques, firstly “magnetostrictive” electrical energy is converted to mechanical energy (or vibration) with a magnetic coil attached to vibrating piece like nickel and Terfenol-D. Secondly for piezoelectric technique, the electrical energy is converted to high frequency electric energy with piezoelectric crystals (rely to material strain) attached to the vibrating piece (sonotrode, probe or horn) (Pilli et al., 2011).

1.2 Cavitation

Cavitation is the phenomena of the formation, growth and collapse of microbubbles or cavities occurring in extremely small interval of time (milliseconds) in a liquid (Shah et al., 1999). Caviation can generate in two ways, if caviation occur by passage ultrasonic waves, it is acoustic caviation or ultrasonication and if it occur due to pressure variation in liquid, it is hydrodynamic caviation. By collapse of cavities, a large amount of energy will be released and according to the ‘hot spot’ theory, When bubbles collapse was happened, pressure can reach to 500-10,000 atm and temperature reach to 3000- 5000°K (Patil et al., 2007; Gogate el al., 2003). Consequently, in these extreme condition, hydroxyl (OH°) and hydrogen (H°) radicals would be formed by thermal dissociation of water and oxygen (Jiang el al., 2002). These radicals penetrate into water and oxidize dissolved organic compounds. Hydrogen peroxide (H_2O_2) is formed as a consequence of OH° and $HO_2°$ radical recombination.

US increases transport of small molecules in a liquid solution by increasing the convection in an otherwise stagnant or relatively slow moving fluid (Nyborg, 2001). It also can increases convection in liquid by two mechanisms. The fist mechanism is micro-streaming. Cavitation sets up eddy currents in the fluid surrounding the vibrating bubbles and the eddy currents in turn exert a twisting and rotational motion on nearby cells. In the vicinity of vibrating gas bubbles intracellular organelles are also subjected to rotational forces and stresses. This microscopic fluid movement is called micro-streaming. In the micro-streaming, the cycles of low and high acoustic pressure because the gas bubbles to expand and shrink which in turn creates shear flow around the oscillating bubbles (Nyborg, 1982). The second mechanism of enhancing convection is acoustic streaming that momentum from directed propagating sound waves is transferred to the liquid, causing the liquid to flow in the direction of the sound propagation (Starritt, 1989). By US irradiation applications, a number of mechanical, acoustical, chemical and biological changes occur in a liquid due to acoustic cavitation (Chua et al., 2010; Laborde, 1998). In this study, the feasibility and efficiency of different applications of US technique as a free-chemical and environmental friendly process for water treatment were evaluated.

2 Methodology

2.1 Application of ultrasound for membrane filtration

Membrane technologies are now widely accepted as suitable process for separation solids from liquid due to its high removal capacity and ability to meet multiple water quality objectives. The most common membrane processes are microfiltration (0.1-10 micron pore size), nanofiltration (2-100 nm pore size), ultrafiltration (0.5-2 nm pore size), electrodialysis, and reverse osmosis (<0.5 nm pore size) (Lamminen, 2004). Some advantages of this technology are effective in easier to be automated, compact, removing pathogens, requiring less coagulating agents and disinfectors, simpler to maintain and capable of producing high-quality drinking water for human consumption (Lu et al., 2009). In addition to these advantages, membrane filtrations have some operation problems such as concentration polarization and fouling which fouling is more pronounced. Membrane fouling is a process where solute or particles such as natural organic matter, silica, iron oxides, calcite, and clays deposit onto a membrane surface or into membrane pores in a way that degrades the membrane's performance (Zhang et al., 2003).

In ultrafiltration and microfiltration, fouling mechanism could be occur in three ways such as formation of cake layer on membrane surface, adsorption of fouling material in pore walls or on the membrane surface and blocking the membrane pores (Pirkonen et al., 2010). Due to membrane fouling, permeate flux is declined and resistance of membrane will be increase (Kyllonen et al., 2005). Fouling could affect on water quality and quantity that passing through membrane and in result life time of membrane would be shortness (Seidel and Elimelech, 2002). There are four various types of fouling: colloidal (clays, flocs), biological (bacteria, fungi), organic (oils, polyelectrolytes, humics) and scaling (mineral precipitates) (Ashaghi et al., 2007). Physically, biologically or chemically methods can be used to clean membrane. Physical cleaning includes sponges, water jets or back-flushing. Biological cleaning uses biocides to remove all viable microorganisms, whereas chemical cleaning involves the use of acids, alkalis, surfactants, sequestrates and enzymes to remove foulants and impurities (Zeman et al., 1996). These methods have some disadvantages. For example, chemical cleaning of membranes results in increased cost and disposal of waste chemicals and cause secondary pollution. In backflushing system, membranes would expose to repeated backflushing/backwashing cycles typically and experience degradation in maximum flux. Also, for backflushing/backwashing and chemical cleaning the filtration process must be shut down that it is an undesirable for continues operation (Li et al., 2002; Chen et al., 2006). Due to existing of these problems, US technology has been demonstrated effective for membrane cleaning. Using US for cleaning membrane have some advantages such as online operation(during the filtration time can be use), without any secondary pollutant and transportation and handling problems, enhancing disinfection of the distribution systems due to present hydrogen peroxide (H_2O_2) and hydroxyl free radical (OH°) that produced by US. Most ultrasonic cleaning devices work on the principle of cavitation phenomena. Due to this phenomena, acoustic streaming, microstreaming, microstreamers, microjets, and shock waves could generated that may be capable to preventing the deposition of particles that lead to fouling and dislodge particulate matter from membrane surfaces and enhance the dissolution of substances due to the increased mass transfer of liquid to surfaces (Le et al., 2002; Verraes et al., 2000).

Lu and collogues (2009) applied focused US beams of about 2.7 MPa (peak) pressure and 671 kHz frequency to clean membrane. The beam has 300 cycles per burst with about 50 Hz pulse repetition rate for the bursts to avoid damaging to the transducer (V301-SU, Panametrics, Inc). Before fouling, filtration rate was 3.47 mL/min and after cleaning by US beam filtration rate was restored to about 1.67 mL/min. One study was shown that ultrasonic frequencies from 70 kHz up to 620 kHz were able to clean ceramic membranes without damaging them (Lamminen, 2004). Kobayashi et al., (2003) found that by cross-flow systems operating in an US field can clean microfilter and ultrafilter. Other study was shown that US can enhance membrane distillation up to 200% with an ultrasonic intensity from 0 to 5W/cm^2 (Zhu and Liu, 2000).

In Table 1, some investigations that were performed to evaluation of efficiency of this technique for membrane filtration are illustrated. Each investigation has the specific US power and frequency and flow rate and membrane type.

Table 1 Various application of US technique for membrane filtration

Important results of investigation	Frequency(KHz)	Power (w)	Reference
At 40 kHz sonicating for 10 minutes, the permeate flux was restored to over 95% of the initial filtration flux. Membrane pore dilation and breakage were observed at 12.3 kW/m^2 power density and 40 kHz frequency.	40 , 68, 170	0 to 500	Li et al., 2011
During ultrafiltration process, 28 kHz sonication provides more 50% flux rate than absence of US. In cleaning process, 28 kHz sonication recovers more 200% flux rate than absence of US.	28, 45, 100	100	Cai et al., 2010
More effective control of membrane fouling occurred at high pH, low ionic strength, and in the absence of divalent cations.	20	9.2±0.4	Chen et al., 2006
On average, the permeate flux increased 50.8% for a 500 mg/L$CaSO_4$ solution and 69.7% for a 1000 mg/L CaSO4 solution, about 215% for a $FeCl_3$ solution with 20 mg/L Fe^{3+} and 264% and 113%, for a 500 and 1000 mg/L CMC solution during 3 h of filtration in the presence of US.	20	170	Feng et al., 2006

Different investigations on the application of US technique for membrane cleaning were performed, but approximately all of them have been in laboratory scale. In fact, this technology are facing to two challenge, the first is the cost of energy needed would be high and the second is US transducers such as lead zirconate titanate ceramics that could handle a high power to produce cavitations would be costly, bulky and brittle (Lu et al., 2009).

2.2 Application of ultrasound for turbidity and total suspended solid reduction

Turbidity is a principal physical characteristic of water. It is caused by suspended substances or dissolved substances such as clay, silt, finely divided inorganic and organic matter, soluble colored organic compounds, plankton and other microscopic organisms (EPA, 1999). Conventional methods for reduction turbidity and Total Suspended Solid (TSS) in water treatment process are rapid and slow filtration, microfiltration, ultrafiltration and coagulation/flocculation. In recent years, some studies on application of US for reduction of turbidity and TSS were carried out. An experiment with variation of time, power, and variation of frequency of US irradiation was performed. Time period using 0.5, 1, 1.5, 2 and 2.5 hours and four conditions of frequency and power 20 kHz 25 W, 28 kHz 30 W, 45 kHz 40 W, and 200 kHz 100 W were applied. Figs. 1 and 2 are shown the highest efficiency at the various conditions. The most effective frequency of the variation was 28 kHz with 75% efficiency in 40 Watt of power while the most effective power was 60 Watt with 76% efficiency at 28 kHz of frequency.

Also, the reducing of turbidity at 28 kHz of frequency at 1 hour of irradiation time with variation of power was investigated (Fig. 3). It is clearly demonstrated that for 28 kHz frequency, highest turbidity reduction (76%) is at 60W (Mutiarani et al., 2009). In other study, US generator operating at 27.2 kHz frequency at 30 second reduction of turbidity in various pressures was investigated (Fig. 4). It was found that water turbidity decrease by 4 times compared to initial turbidity of 39NTU. Also, affects of irradiation duration of turbidity reduction is shown in Fig.5 and it is clearly shows that in 5 second sonic water treatment, turbidity decreases 5-7 times (Stefan and Balan, 2011).

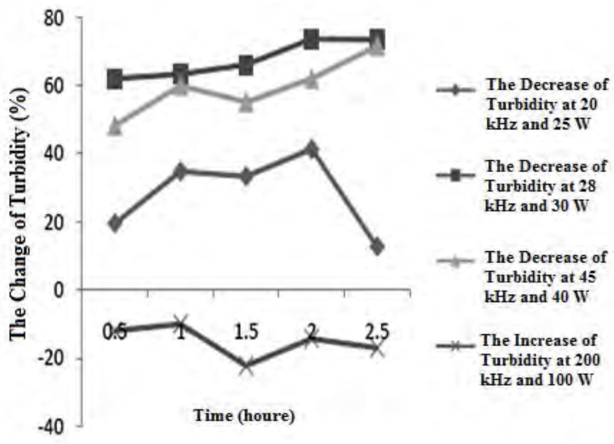

Fig. 1 The Changes of Turbidity in Some Variations (Mutiarani et al., 2009).

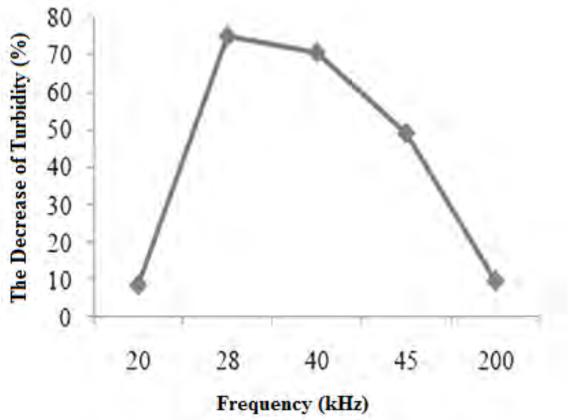

Fig. 2 Turbidity reduction at 40 W of and 1 Hour Irradiation with Variation of Frequency(Mutiarani et al., 2009).

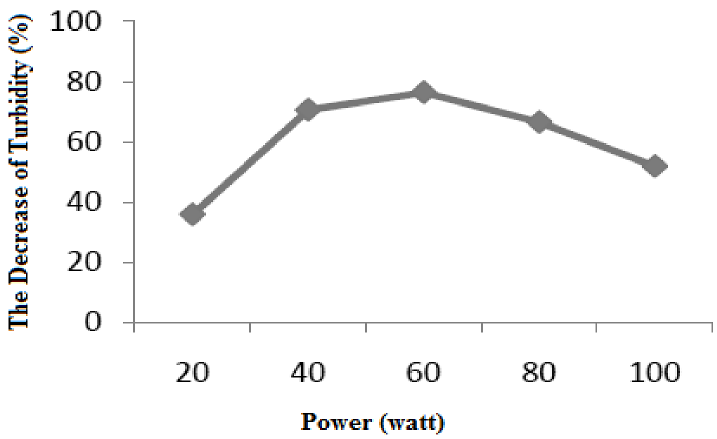

Fig. 3 The Decrease of Turbidity at 28 kHz and 1 Hour of Irradiation time with Variation of Power (Mutiarani et al., 2009).

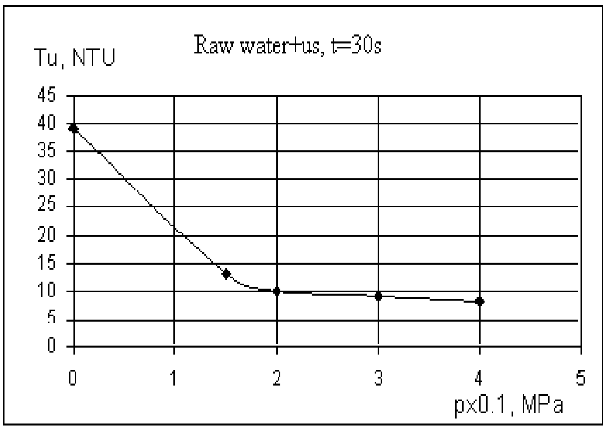

Fig. 4 The turbidity variation depending on the supply pressure of the US air-jet generator (Stefan and Balan, 2011).

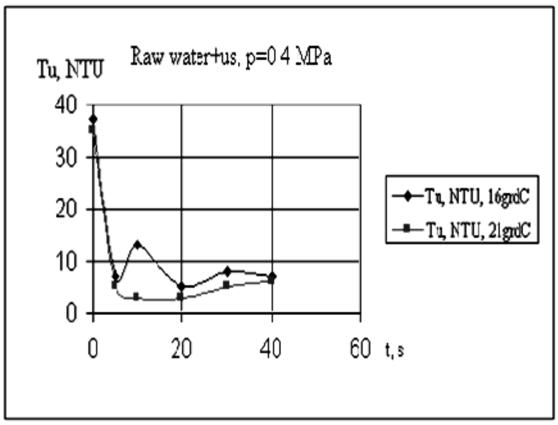

Fig. 5 The turbidity variation depending on the irradiation time (L=131 dB, f = 27,2 kHz) (Stefan and Balan, 2011)

One study on the reduction of TSS due to various power density ultrasonic irradiation was shown that for all power density the TSS percentage reduction increased significantly at 30min ultrasonic irradiation but became unstable from 60 min to 120 min of irradiation at all power density. The highest percentage reduction was 84% which fall at 0.024 W/cm^3, 120 min while the lowest percentage reduction was 60% at 0.06 W/cm^3 for 60 min (Chua et al., 2010). Wang and collogues have studied US/modified clay process to remove blue algae from the artificial waters and were found the removal efficiencies of turbidity about 85.42% (Wang et al., 2008). Liang and collogues were found that turbidity of raw water from 10.3 NTU was reduced to 1.48 NTU by coagulation and 0.881 NTU by 15s ultrasonic irradiation at 40 kHz 60W as pretreatment for coagulation (Liang et al., 2009).

2.3 Application of ultrasound for algae removal

Algae growth is the common problem in the water treatment plants and water reservoir. Algae are aquatic organisms classified separately from plants. Algae are a large and diverse group of simple, typically autotrophic organisms, ranging from unicellular to multicellular forms, such as the giant kelps that grow to 65 meters in length. The main factors that influence algae growth are temperature and light (Allen and Arnon, 1995; Sayadi et al., 2011). Some types of algae are green algae, the red algae, the diatoms, brown algae and the flagellate algae. Exist of bloom concentrations of algae cause some problems such as increased coagulant demand and treatability, taste and odour issues, filter blocking and toxin release (Henderson et al., 2008). There are various strategies to control and remove algae from water such as, dissolved air flotation, covering of basins and filters, advanced oxidation processes, ozonation, coagulation/flocculation by copper sulphate and potassium permanganate, bubble curtains, pulsed sludge blanket clarification, aeration, pre-oxidation using chlorine, ozoflotation, catalytic processes, barley straw and (Haarhoff and Edzwald, 2004; Kommineni et al., 2009). According to EPA survey on 76 utilities in 2009, best method for control algae growth and was mechanical equipment prone to assist algal growth and cleaning of basins, chlorination for disinfection, use an occasional shock treatment, and addition of algicides in-situ in reservoirs (Kommineni et al., 2009). A novel technique for control algae growth is ultrasonic irradiation. US can destroying the algae by initially physical pathways that the main destroying performed by cavitation phenomena. Control mechanisms that was reported may be consist of: production of free radicals, disruption of gas vesicles and inhibition of photosynthesis (Lee et al., 2002). One study in laboratory scale by US irradiation frequency of 42 kHz at 30, 60, 90, 120 and 150 seconds of irradiation ,were shown that respectively 8.55, 35.22, 67.22, 90.67 and 100% of the algal population were destroyed (Mahvi and Dehghani, 2005). Most study on US usage was focused on cyanobacterial species and *Microcystis aeruginosa*. In some study kill rates of 90% using US frequencies between 20 kHz and 1.7 MHz was reported (Tang et al., 2003; Hao et al., 2004). Diane Purcell was found that cyanobacterial cell counts were reduced from 40% in the control system to 18% in the test systems where US was applied. Also reduction was obsereved from 19% and 15% for green algae and from 32% to 29% for diatoms respectively (Purcell D, 2009). Study on degradation of Microcystins was performed in order to evaluate the efficiency and feasibility of the combined US-UV catalytic system for removal of Microcystins from polluted water. Result were shown that in combined process, the removal efficiency of Microcystins-LR and Microcystins-RR reached 20% and 18% respectively in the first 20 min and approximately 100% in 120 min of irradiation at 20 kHz frequency (Qiu et al., 2011). Although increase of some types of algae was reported that 67% increase of *Microcystis sp* during continuous application of US at a frequency of 28 kHz and power 20 W and 60% increase of *Spirulina platensis* after a pulse of 12 minutes every 11 days of 1.7 MHz US frequency was reported (Tang et al., 2003). Result of other investigation on application of US to improve the removal by coagulation of *Microcystis aeruginosa* by UV254, and chlorophyll was shown that removal efficiency is depending on coagulant dose and US conditions so by 5s of ultrasonic irradiation and 0.5mg/l coagulant, removal efficiency increase from 35% to 67% and most effective US intensity was 47.2W/cm^2, and the highest removal efficiency of *Microcystis aeruginosa* was 93.5% by the this combination method (Zhang et al., 2009). Influence of ultrasonic field on Microcystins in other study was investigated. Three Microcystins solutions (2 g/L) were exposed to ultrasonic irradiation at 20 kHz with different ultrasonic powers of 0, 30, 60, and 90W at various times 5, 10, 15, 20 min. Removal of Microcystins dissolved in water in these condition is illustrated in Fig. 6. It is clear that highest removal were obtained at 90 W after 20min sonication. Also, removal efficiency of four same solution at 30W and different frequencies of 20, 150, 410 kHz and 1.7 MHz for different times is shown in Fig. 7. It could be found that highest removal was at 20 kHz after 20 min sonication (Bozhi M et al., 2005).

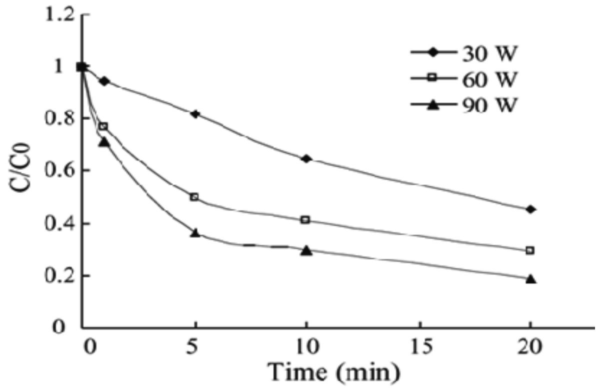

Fig. 6 Removal of microcystins dissolved in water due to sonication at 20 kHz and different powers and times . (Bozhi M et al., 2005).

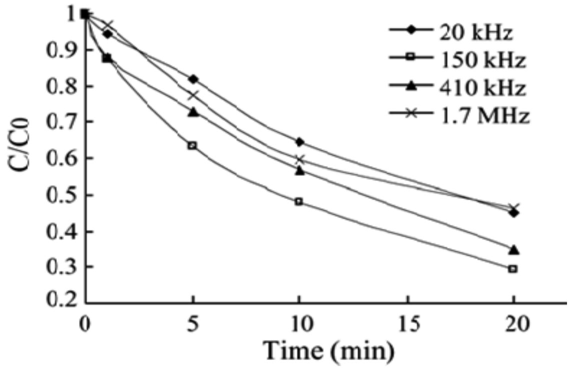

Fig. 7 Removal of microcystins dissolved in water due to sonication at 30 W and different frequency and time. (Bozhi M et al., 2005).

2.4 Application of ultrasound for water disinfection process

The water disinfection process is fundamental to remove microorganisms and can be done by different methods such as use of Ultraviolet and chemical substances, like are chlorine, hypochlorite, chloramines, chlorine dioxide, bromine and ozone (Kim et al., 2002; Pozos et al., 2004). Their effectiveness can be considered respectively: ozone≥chlorine>bromine>chlorine dioxide>hypochlorite>chloramines (Masschelein, 2002). There is a trend within the water treatment industry to develop and employ more environmentally responsible technologies to help the lower impact of chemicals in effluent waters and prevent from product DBP_S such as Trihalomethanes and haloacetic acid. Therefore utilization of US technique for disinfection process was investigated by many researchers (Gomez-Lopez et al., 2009; Toor et al., 2007). US irradiation can inactive microorganism in several mechanism that is based on the acoustic cavitations. The first mechanism could be chemical attack by the hydroxyl radicals that generated by US, secondly high pressure and temperature resulting from bubble collapse that can causing cell death and third shear forces induced by microstreaming occur within and consequently damage bacterial cells. Also, while cell membrane were ruptured due to US irradiation, chemical oxidants can diffuse into the cell and destroy the microorganism structures (Joyce et al., 2003). US technique in many studies has investigated in different condition such as alone disinfection process, as pretreatment or combined by other disinfection methods such as UV, chlorine, Ozone for water disinfection. Hulsmans and colleague have evaluated the effects of process parameters ultrasonic water disinfection system. While higher flow rate, higher electrical power and higher specific energy results in faster bacterial removal, also higher initial bacterial inoculum requires longer treatment time to achieve the same final bacterial level (Hulsmans et al., 2010). Viability of ultrasonication, hydrodynamic cavitation and hybrid cavitation processes involving the use of chemicals like hydrogen peroxide and ozone along with cavitation were investigated while US were carried out with an ultrasonic horn (Supersonics) which operated with a 22 kHz 240 W. Efficiency of these disinfection techniques is illustrated in Table 2. It is clear that by application of US and chemicals, higher reduction was achieved (Jyoti et al., 2003).

Table 2 Percentage disinfection obtained for various techniques (Jyoti et al., 2003).

Disinfection technique	% Reduction in Total coliforms		% Reduction in Fecal coliforms		% Reduction in Fecal Streptococci	
	15min	60min	15min	60min	15min	60min
5 mg/l H_2O_2	13	28	9	21	9	20
2 mg/l O_3	60	94	78	100	74	97
US-horn+5 mg/l H_2O_2	65	-	90	-	84	-
US-horn+2 mg/l O_3	99.6	-	99.3	-	98.4	-
US-bath+5 mg/l H_2O_2	95	-	96	-	88	-
US-bath+2 mg/l O_3	98.3	-	97	-	97	-

Application of 20 and 850 kHz US as pre-treatment and simulation process to improve efficiency of sodium hypochlorite for *E. coli* inactivation were performed. The application of 850 kHz US as pre-treatment, could be very effective at 1 min exposure and by application of 20 kHz US as simulation treatment applied with chlorination is better using a short period. However disinfection by less energy consumption is more attractive, so simulation process can be more effective (Duckhouse et al., 2004). In other study effect of ultrasonic pretreatment operating at 500W and 20 kHz on chlorine dioxide (ClO_2) disinfection efficiency was investigated. Inactivation rate of various processes at various powers is shown in Figure 8. It is clear that by US application, higher inactivation could be achieved (Ayyildiz et al., 2011).

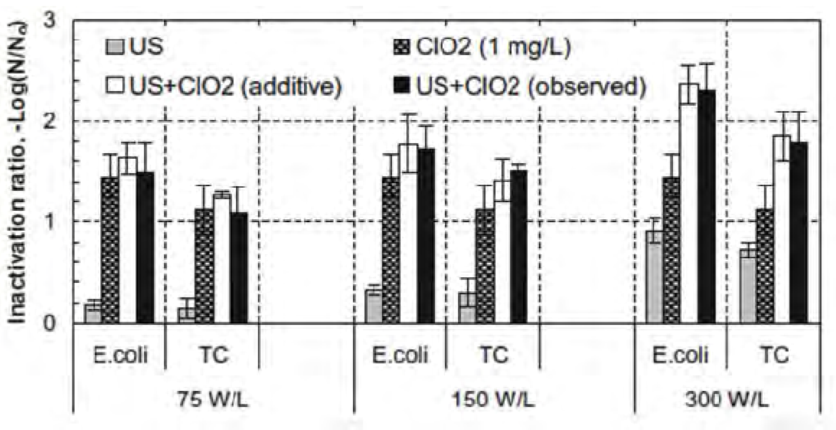

Fig. 8 Inactivation of E. coli and TC by US, ClO2, and their sequential combination (Ayyildiz et al., 2011).

The application of US operating at 36 kHz and 200 W in absence and present of 1.0 g/ml titanium dioxide (TiO_2) were evaluated for inactivation of Legionella (Fig. 9). As shown the study, without TiO_2 only 18% of viable cells of Legionella were inactivated, while, with TiO_2 97% were inactivated after 30 min (Shimizua et al., 2010).

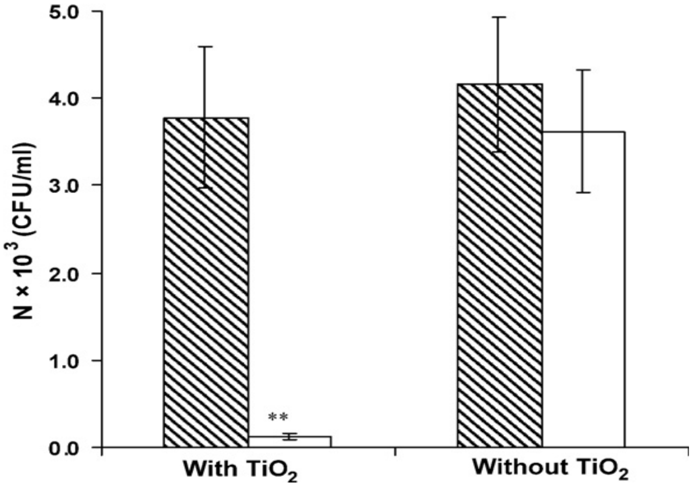

Fig. 9 The effect of TiO_2 on the number of remaining viable Legionella cells before (shaded columns and after a 30-min US treatment (open columns) at a concentration of TiO_2 of 1.0 g/ml (Shimizua et al., 2010).

Operation condition and important results of different study on US application for water disinfection process has been presented in Table 3.

Table 3 Diffrent application of US for water disinfection process.

Disinfection process	Inactive Microorganism	Operation Condition	Irradiation Time(min)	Removal Efficiency (%)	Reference
US	Cryptosporidium parvum oocysts	1 MHz, 4.1 W	2, 4	87.8, 94.02 respectively	Olvera et al., 2008
US	E .coli	24 kHz, 160 W	120	92.3	Paleologou et al., 2007
US +25-50 mg/l H_2O_2	E. coli	24 kHz, 160 W	120	99.99	Paleologou et al., 2007
US	E. coli	42 kHz, 70W	1, 15, 30, 45, 60, 75, 90	0, 78.3, 87, 98.0, 99.6, 99.7, 99.80	Dehghani, 2005
US	E. coli XL1-Blue	27.5kHz, 42 W/ml	3	99	Furuta et al., 2004
US + 1mg/l TiO2	E. coli	39 KHz, 200 w	30	98	Dadjour et al., 2005
US + Electrolysis	Klebsiella pneumonia	40 kHz	15	100	Joyce et al., 2003
US	B. subtilis	27 kHz, 300 W	60	96	Mason et al., 2003

2.5 Application of ultrasound for water softening process

Water hardness is known as existence of bivalent and trivalent cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and in lower traces; aluminum (Al^{2+}, Al^{3+}) and iron (Fe^{2+}, Fe^{3+}) that among these cations, Ca^{2+} and Mg^{2+} are the main factors of hardness (Kabay et al., 2002; Ildiz et al., 2003). Water hardness cause some problems such as scale formation in pipes and cooling tower, reaction by soap and formation hard foam and decrease heat change capacity and membrane clogging (Ghizellaoui et al., 2004; Park et al., 2007). Conventional methods for hardness removal are lime-soda process, ion exchange, electrocoagulation, electrodialysis and nano-filteration. Entezari and Tahmasbi used combined US irradiation operating at 20 kHz and ion exchange process for hardness removal from water. They used styrene-divinylbenzene co-polymer with sulfonic acid group as a strong acid cation resin. Effect of different parameter such as contact time, amount of sorbent, temperature and ion concentration were investigated (Entezari and Tahmasbi, 2009).

2.6 Application of ultrasound for other pollutants removal

Use of US technique for removal various pollutants from water was investigated in different researches. Thangavadivel and colleague have removed DDT [1,1,1-trichloro-2,2-bis(p-chlorophenyl) ethane] at initial concentration 8mg/L from water at low power high frequency US (1.6 MHz, 150 W/L). After 45min treatment, concentration was reduced to 1.2 mg/L and after 90 min, concentration was reduced to 1 mg/L (Thangavadivel et al., 2009). Guo and colleague have studied the removal of four halomethanes such as $CHCl_3$, CCl_4, $HBrCl_2$ and $CHBr_2Cl$ at initial concentrations 15.79, 10.43, 3.19 and 4.75 µg/l respectively by application of 20 kHz and 500W US from very low initial concentration chlorinated drinking water. The results were shown that after 1 hour US irradiation, 48.2% of $CHCl_3$, 64.6% of CCl_4, 58.3% of $CHBrCl_2$ and 54.6% of $CHBr_2Cl$ were removed, respectively (Guo et al., 2006). In other study, degradation of two aldehydes component such as benzaldehyde (C_6H_5CHO) and formaldehyde (HCHO) at initial concentration about 8.2×10^{-4} mol/L by US irradiation at 200 kHz, 200 W and combined process as US+UV+ TiO_2 were investigated. Concentration of TiO_2 was 1g/L and UV main wavelength was 365 nm (Fig. 10).

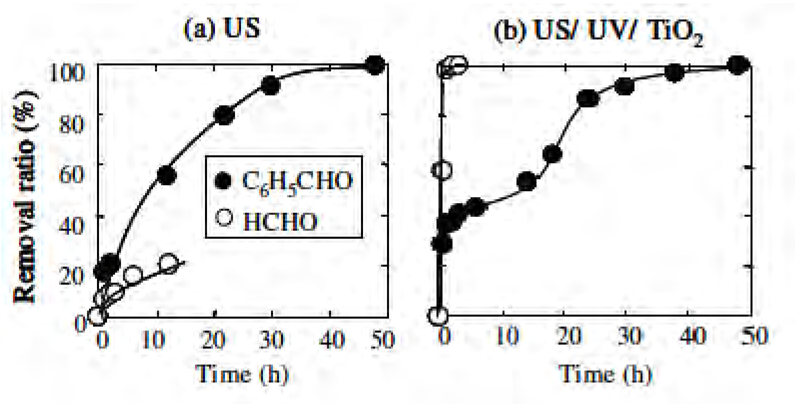

Fig. 10 Removal ratio of aldehydes under conditions of (a) and (b) (initial concentration of aldehydes: 8.2×10^{-4} mol/L) (Sekiguchi et al., 2011)

According to the Fig 10, it is clear that removal ratio of HCHO by US was lower than that of C_6H_5CHO (Sekiguchi et al., 2011). Mendez-Arriaga et al. (2008) have studied the degradation of 2-[3-(2-methylpropyl) phenyl] propanoic acid, that commercially available as ibuprofen (IBP) by US irradiation operating at 300 kHz, 80W in polluted water. They were achieved to 98% degradation of IBP by initial concentration about 21 mg/L after 30 min treatment (Mendez-Arriaga et al., 2008). Influence of US field on iron components such as Fe^{2+}, Fe^{3+}, Fe_{og} removal from water was evaluated in one study. US irradiation was generated at 22 and 24 kHz with 180 and 300 W at 1 and 5min sonication time. Results were demonstrated that 5 min sonification of water samples had the effectiveness amounting to 15% to over 30% for oxidation of Fe^{2+} and in 1 min sonication, oxidation effectiveness were blow 10% (Stegpniak et al., 2008). Removal of NH_4-N, COD_{Mn}, and other pollutants of micro-polluted raw water was investigated by combination of US and zeolite Granular Active Carbon (GAC) filter as a pre-treatment of raw water. Zeolite GAC filter was operated at 30 min hydraulic retention time (HRT) combined to US that were operated at constant frequency of 20 kHz for 30 min treatment by 8min running, 2min pause period. The results were demonstrated that removal rate of NH_4-N, COD_{Mn}, colourity and turbidity were about 96.5%, 54.24%, 91% and 88% respectively, better than that of without US process (Yang and Peng, 2011). The degradation of 2-chloropyridine in water was studied using UV lamp (254 nm, 110 W) and US irradiation at a fixed frequency of 20 kHz and a variable applied power up to 250 W. The result is shown the degradation was about 90% 2chloropyridine after 300 minutes ultrasonic irradiation (Stapleton et al., 2005).

3 Conclusions

The main cause of US efficiency may be the cavitation phenomena that accompanied by generation of local high temperature, pressure, and reactive radical species (OH°, HO_2°) via thermal dissociation of water and oxygen. Amount of hydroxyl radicals in the sonolysis system is directly related to the degradation efficiency, because oxidation by hydroxyl radical is the main degradation pathway. The most experiments of US technique were carried out at laboratory scale due to its cost. Although this technology in some aspect such as algae removal was used in full scale and having the high efficiency. The cost of US techniques must be decreased suggesting utilization of solar energy. There are various parameters that can affect to application and efficiency of US in water treatment such as power density, frequency and irradiation time. Although for each special application of US, experimental results are needed for obtain the optimum power density, frequency and irradiation time to reach cost-effective and high application efficiency. It would be suggested that the US technique could be extended to clean up of other polluted parameters in water and environment.

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