POTENTIAL FOR APPLICATION OF ULTRASOUND IN THE WASTEWATER TREATMENT PROCESS

Krishnan Balasubramaniam, Chandra Abesingha, and Srinivas B. Kumar
Department of Aerospace Engineering
Mississippi State University

INTRODUCTION

It is easy to remove large particle contaminants in fluids by conventional filtration processes. However, for contaminants in the range between 0.1 to 100 micro-meters in diameter, the filtration process becomes inefficient (Strauss 1980). Methods commonly used such as sedimentation, centrifugation, and flotation rely on density difference between the solid contaminant and the fluid. Electrophoresis process relies on the electrical charge borne by the solids. Apart from these special property requirements, the process time taken by these conventional methods is often prohibitively long. Furthermore, if the particles are very small, Brownian motion appears. This is a random movement imparted to the particle by collisions between the particle and the molecules of the surrounding fluid. This effect becomes appreciable at particle sizes of about 2 to 3 micro-meters and predominates over the force of gravity when the particle size is on the order of 0.1 micro-meter or less (Apfel 1988). The random Brownian movement of the particle tends to suppress the effect of the force of gravity and, hence, also contributes to an increase in the time of particle settlement. These non-settleable solid particles can be converted into larger and heavier settleable solids by physical-chemical changes. This is currently brought about by adding and mixing chemical coagulants into the raw water. The coagulated solid particles are then removed by sedimentation or filtration. In this paper, an ultrasonic/acoustic agglomeration technique is discussed for assisting the coagulation/flocculation process of fine particles suspended in water.

Biological treatment methods use microorganisms to treat wastewater. Even though there are several methods of biological treatment, activated sludge process is the most commonly used and the most efficient secondary wastewater treatment method, treating approximately 75% of the total wastewater flow in the USA (Boczar 1992). Research has shown the potential application of ultrasonics in several branches of environmental engineering, namely, purification of water by killing bacteria and dewatering of sludge (Ensminger 1989). Information exists in the literature on previous studies regarding enhancement of biological reactions using ultrasonics (Bar 1988; Zabaneh and Bar 1991). These studies have shown that the effect of ultrasonics can be destructive or constructive to the rate of biological cell growth, depending on the intensity of the ultrasonic energy applied and that ultrasonic energy at sufficiently low levels could stimulate cell activities. An increase in the efficiency of the microorganisms in a wastewater treatment process could potentially lead to: (a) a greater degree of purification, (b) a reduction of treatment system size, (c) decrease in treatment duration, and (d) reduced pre- and/or post-treatment. The mechanisms contributing to the enhanced activity of the sludge are the micro-streaming effects as well as the shearing effects of the ultrasound.

BACKGROUND

The physical mechanisms of ultrasonic interaction with materials are: (1) physical, (2) chemical, and (3) thermal. The basic physical mechanism related wave propagation including standing wave patterns, bubble oscillation causing cavitation and Bernoulli's forces, and bulk effects such as decrease in effective viscosity, micro-streaming, and inter-particle shearing. The domination of one or more of these effects will depend upon the frequency-target size ratio as well as the geometrical and intensity characteristics of the ultrasound generation. In this section, the several technical issues associated with the ultrasonic phenomena and various physical principles used in the proposed research will be briefly discussed.

Like all wave, ultrasonics exerts a radiation force in the medium of propagation which can be exploited to preferentially move the medium or fraction of the medium in a controlled direction. Reflection at interfaces between different media may lead to standing waves and preferential migration of particles towards the nodal or antinodal planes. The agglomeration process can be attributed to a combination of the Orthokinetic, Van der Waal's, and Bernoulli's forces between particles in the fluid medium as described in more detail below.

Ortho-kinetic Forces. When ultrasonic standing waves, at appropriate intensity, are passed through suspended particles in water, the particles first start vibrating with the sound and then start to migrate to the anti-nodal/nodal regions of standing waves. The migration of the particles is due to the non-uniform distribution of the pressure and velocity components in standing wave field. Vibration of the particles along with the fluid depends on the size of particles and frequency of the sound waves. At low frequencies, the particles vibrate with the sound and tend to lag when the frequencies are increased. When the frequency is very high the larger particles remain almost stationary, while the smaller particles follow the vibration. The maximum size of particles which vibrate along with the sound at a particular frequency is called the critical particle size for that frequency (Yosioka et al. 1955).

Hydrodynamic Forces. When ultrasound is applied on a fluid with suspended particles, acoustic streamlines pass between particles. Due to the Bernoulli's effect, in the constriction zone between the particles, the flow velocity increases and the pressure drops, resulting in an attraction force between the particles. When the attractive force due to the Bernoulli's effect is higher than the repulsive force (due to the similar polarity of surface electrical charge on these particles) the particles agglomerate (Mandralis and Feke 1993; Whitworth et. al. 1991).

Van der Waal's Forces. Van der Waal's forces exist between all particles in nature and tend to pull any two particles together. This attracting force acts opposite to the Zeta potential. As long as the Zeta potential is stronger than the Van der Waals force, the particles will remain suspended. This mechanism becomes more predominant when the particle sizes are very small.

LITERATURE BACKGROUND

The response of micron-sized particles for various combinations of acoustic, gravitational, and diffusion forces has been experimentally studied (Hagashitani et al. 1981; Tolt and Feke 1991) and modeled (Haar and Wyard 1978; Weiser and Apfel 1982; Tolt and Feke 1988; Mandralis et al. 1990; Collas et al. 1989; Gould et al. 1992). It has been suggested by Tolt (1990) that the diffraction of the transducer and reflector surfaces is responsible for the creation of guided standing waves which have a non-uniform distribution of acoustic velocity and pressure along nodal planes. These non-uniform pressure and velocity variations are responsible for driving suspended particles to anti-nodal/nodal regions.

Tkachuk et al. (1989) studied the possibility of using ultrasound to intensify the activity of different bacteria used in the activated sludge process. According to this study, the ultrasonic waves at low intensities can increase the activity of microorganisms in an activated sludge reactor system. Bar (1988) investigated the effect of ultrasound on bioprocesses. Cells of Rhodococcus Erythropolis ATCC 25544 were used in this study to oxidize cholesterol. Sonication was applied in a pulsed mode in order to eliminate the heat generation. It was observed that 99% conversion was achieved in 1.0 and 2.5 g/l of cholesterol after 16 hours and 24 hours respectively at a power level of 2.2 W/cm^2 for 5s. duration pulse applied every 10 minutes. Corresponding unsonicated samples showed only 63% and 50% at 16 hours and 24 hours time periods respectively. Zabaneh and Bar (1991) further investigated the ultrasound enhanced bio-processes using Arthrobacter Simplex ATCC 6946 for dehydrogenation of hydrocortisone. The experiment was performed with immobilized cells and it was found that ultrasound enhancement of bioconversion was quite significant and no ultrasound induced disruptive damage occurred to the gel beads. The explanation for this significant ultrasound enhancement was that when the diffusivity is slow in a solid media, such as in gel beads, further facilitation of the substrate diffusion process could be more readily achieved.

EXPERIMENTAL APPARATUS

The experimental setup, as shown in Figure 1, consists of two bench scale reactor tanks. One of the reactors has an ultrasonic generator at the appropriate location, while the other was used as a control sample (no ultrasound transducer). Both the tanks were fabricated from acrylic sheets and are designed in such a way that their dimension along the width can be varied according to the requirement. A special clamping device was used to position and move the ultrasonic transducer inside the water tank. The ultrasonic transducer surface was aligned parallel to the reflecting surface and the distance between them was adjusted to match the selected multiple of the wave length which varied from five to ten times the ultrasonic wave length in ambient water.

The power amplifier (Wilcoxon PA8B series) and the function generator (Wavetek model 134) were used to excite the ultrasonic transducer. Submersible ultrasonic transducers from AIRMAR Technology Corporation (50 KHz. and 120 KHz.) were used to generate ultrasonic standing waves in water. A digital multi-meter was used to measure voltage/power and a Tektronix 320 digital oscilloscope was used to measure and monitor the input frequency to the transducer.

A similar instrumentation and set-up was used for the activated sludge experiments.

EXPERIMENTAL PROTOCOL

For the experiments on particle agglomeration, two reactor tanks were filled with the measured quantity of water which has zero turbidity. Kaolinite was used as the particulate contaminant. Kaolinite is a form of clay which has a slow settling rate in water just like several other forms of clay. The particle size of the Kaolinite ranged from 2 to 10 microns. A known quantity of Kaolinite was mixed and stirred until the particles were evenly mixed. After stirring, the two tanks were left undisturbed for some time until a steady state condition was achieved and multiple samples from both the tanks measured equal turbidity. The ultrasonic generator (located in the ultrasonic reactor tank at selected wave length) was then turned on. The other tank contained the control sample which was used for monitoring the rate of settling due to gravity. Samples were periodically collected from different locations in the two tanks in test cells and measured for turbidity. Every experiment was repeated 5 to 8 times, on different days, and the data was analyzed for statistical reliability. The results obtained from these runs had a 3% variation, and the average values of the results were used in the analysis

For the experiments on the activated sludge, the bio-culture was obtained from the wastewater treatment plant in Starkville, Mississippi. Separate batch reactors were maintained for growing the bacteria required for experiments. These stock reactors were maintained as sequential batch reactors. The two identical plexiglass batch reactors had a total volume of 6.9 liters each. The experiments were conducted using a working volume of 4 liters. Equal amounts of air supply were maintained to each reactor using two air flow meters. Ultrasound was applied to the activated sludge in one reactor and the other reactor was used as the control operating under identical conditions except for the sonication. The substrate-removal-rate, the oxygen-uptake rate, the mixed liquor suspended solids and the mixed liquor volatile suspended solids measurements were conducted using standard laboratory procedures.

EXPERIMENTAL RESULTS ON PARTICLES

The agglomeration experiments were conducted in order to demonstrate the feasibility of utilization of standing ultrasonic waves for particle settlement in water. It was also the aim to study critical parameters influencing rate of ultrasonic agglomeration. Figure 2 is a comparison plot showing Kaolinite particle settlement at different input voltages to the ultrasound transducer which were 10, 15, 20, 25, and 30 Volts respectively for a 50 KHz. frequency standing wave. This plot clearly illustrates that the rate of settlement of the Kaolinite particles in the ultrasonic tank is significantly increased when compared to the conventional gravity settling rate observed in the control tank. From the plots, it was concluded that the intensity of the standing wave is one of the critical parameters influencing the acoustic agglomeration phenomenon. For the range of particle sizes and ultrasonic intensities considered, an increase in the ultrasonic intensity results in an increase in the rate of settleability and consequently an increase in the rate of agglomeration.

Figure 3 is a comparison plot showing the Kaolinite particle settlement at two different frequencies standing waves 50 KHz. and 120 KHz. at a constant voltage of 10 Volts. The graph demonstrates that the rate of agglomeration is also dependent on the frequency. This was observed at other intensity levels of the ultrasound standing waves. The experimental results show that the rate of agglomeration at 50 KHz. standing waves was higher when compared to 120 KHz. frequency standing waves for the range of particle sizes used in this study.

EXPERIMENTAL RESULTS ON SLUDGE

Figure 4 shows the variation of soluble COD values as a function of time with and without ultrasonics at different power levels. As shown in these figures, COD removal rate significantly increases due to the ultrasonic treatment. In both the reactors, the initial and the final MLSS and MLVSS concentrations were found to be comparable. This indicates that the substrate removal is due to the consumption by the biomass only and not due to any other factor such as a change in the chemical reactions or the disintegration of cells (resulting in the release of intercellular enzymes to the surrounding medium and thereby causing the oxidation of the substrate). In these experiments, where substrate removal rate was observed, MLSS and MLVSS have been measured after almost all of the biodegradable substrate was removed from both the reactors. Therefore, the MLSS and the MLVSS in both the reactors should be the same even though the rate of substrate removal in ultrasonic test reactor was higher than in the control reactor.

Effect on Mixed Liquor Suspended Solids. Figure 5 shows the variation of the MLSS and the MLVSS concentrations versus time with ultrasonics and without ultrasonics. As shown in the figure, the MLSS and the MLVSS concentrations increase rapidly illustrating the log growth phase in both reactors. Figure 10 also indicates that the MLSS and the MLVSS concentrations in the ultrasonic reactor increase at a higher rate than in the control reactor and then start to decrease earlier than in the control reactor. This indicates the faster utilization of substrate in the ultrasonic reactor. The MLSS and the MLVSS concentrations in both the reactors decrease gradually due to endogenous respiration.

Effect on Effluent Suspended Solids. Figure 6 shows variation of the effluent suspended solids due to repeated sonication at a power level of 50 W for 2½ hours each day for four consecutive days. As shown in the figure, the effluent suspended solid concentration increases due sonication. The figure also indicates that effluent suspended solid concentration rapidly decreases back to the normal level due to refloculation of the floc particles. This data is supported by several published reports that the rapid settling of floc aggregates in activated sludge could be accomplished by applying mild sonication thus allowing the coalescence of the flocs to take place (King and Forester 1990; Banks and Walker 1977). It was also found that the increase in effluent suspended solids due to sonication was relatively unaffected by the cyclic sonication. This observation supports the work by Banks and Walker (1977) who have noted that the floc breakage depends primarily on the ultrasound intensity rather than the duration of sonication.

SUMMARY

It was observed that the rate of decrease in turbidity from the samples obtained from the ultrasonically excited tank was significantly higher when compared to the control samples in the conventional settling tank. The experiments successfully demonstrate that the ultrasonic standing waves will increase the rate of agglomeration of the unsettleable Kaolinite particles in water (2-10 micro-meter range) when compared to conventional gravity settling.

It can be concluded from the studies on activated sludge that activity of the microorganisms could be significantly improved by sonication. This is observed by substantial increase in the substrate removal rate and oxygen uptake rate due to sonication when compared to the control. Viability of cells are not destroyed due to sonication at the intensity levels used in this study. Substrate removal rate was increased with power levels from 9 W to 56 W. Effluent suspended solids increase due to sonication but rapidly return to the control values due to refloculation of the cells and hence will not significantly influence the performance of the ultrasound enhanced biomass wastewater treatment process.

ACKNOWLEDGEMENTS

The authors thank the Water Resources Research Institute of Mississippi and the Department of Interior for funding this work under project G2028-10.

REFERENCES

Apfel, R.E. 1988. Acoustically induced square law forces and some speculations about gravitation. Am. J. Phys. 56(8), 726-729.

Banks, C. J., and I. Walker. 1977. Sonication of activated sludge flocs and the recovery of their bacteria on solid media. J. Gen. Microb. 98, pp. 363-368.

Bar, R. 1988. Ultrasound enhanced bioprocesses: cholesterol oxidation by Rhodococcus Erythropolis. Biotechnology & Bioengineering. 32, pp. 655-663.

Boczar, A.B., et al. 1992. Characterization of enzyme activity in activated sludge using rapid analyses for specific hydrolases. Water Environment Research. 64, pp. 792-797.

Collas P., M. Barmatz, and C. Shipley. 1989. Acoustic levitation in the presence of gravity. J. Acoust. Soc. Am. 86, 777-787.

Gould, R.K., and W.T. Coakley. 1974. The effects of acoustic forces on small particles in suspension. Finite-Amplitude Wave Effects in Fluids, Proceedings of the 1973 Symposium, Copenhagen. IPC Science and Technology Press Ltd, London, UK.

Gould, R.K., W.T. Coakley, and M.A. Grundy. 1992. Upper sound pressure limits on particle concentration in fields of ultrasonic standing wave at megahertz frequencies. Ultrasonics. 30, 239-244.

King, L.V. 1934. On the acoustic radiation pressure on spheres. Proc. Roy. Soc. Lond. 147A, 212-240.

King, R.O., and C.F. Forster. 1990. Effects of sonication on activated sludge. Enzyme Microb. Technol. 12, pp. 109-115.

Kumar, B.S.Y. 1994. Finite element analysis and experimental validation of ultrasonic assisted removal of colloidal particles in fluids. M.S. Thesis, Mississippi State University, MS 39762.

Mandralis, Z. 1993. Fractionation of fine particle suspensions by ultrasonic and laminar flow fields. Ph.D. Dissertation, Case Western Reserve University, Cleveland, OH.

Mandralis, Z., and D.L. Feke. 1993. Continuous suspension fractionation using acoustic and divided-flow fields. Chem. Eng. Science. 48(23), 3897-905.

Mandralis, Z. and D.L. Feke. 1993. Fractionation of suspensions using synchronized ultrasonic and flow fields. A. I. Ch. E. J. 39(2), 197-206.

Tkachuk, N.G., et al. 1989. Intensification of the activity of activated sludge micro-organisms with ultrasound. Soviet Journal of Water Chemistry & Technology. vii, n6, pp. 82-85.

Tolt, T.L., and D.L. Feke. 1988. Analysis and application of acoustics to suspension processing, In Proceedings of the ASME 23rd International energy conversion engineering conference (Ed. D.Y. Goswami), 4, 327-331.

Tolt, T. 1990. Agglomeration and collection of fine secondary phases in flowing suspensions utilizing resonant ultrasonic fields. Ph.D. Dissertation, Case Western Reserve University, Cleveland, OH.

Whitworth, G., M.A. Grundy, and W.T. Coakley. 1991. Transportation and harvesting of suspended particles using modulated ultrasound. Ultrasonics. 29 (Nov.), 439-444.

Weiser, M.H.A., R.E. Apfel, and E.A. Neppiras. 1984. Inter-particle forces on red cells in a standing wave field. Acustica. 56, 114-119.

Yosioka, K., Y. Kawasima, and H. Hirano. 1955. Acoustic radiation pressure on bubbles and their logarithmic decrement. Acustica. 5, 173-178

Young, M. Moo, et al. 1981. Advances in biochemical engineering, reactors and reactions. Springer-Verlag, New York, N.Y.

Zabaneh, M., and R. Bar. 1991. Ultrasound-enhanced bioprocess II: Dehydrogenation of hydrocortisone by arthrobacter simplex. Biotechnology and Bioengineering. 37, pp. 998-1003.

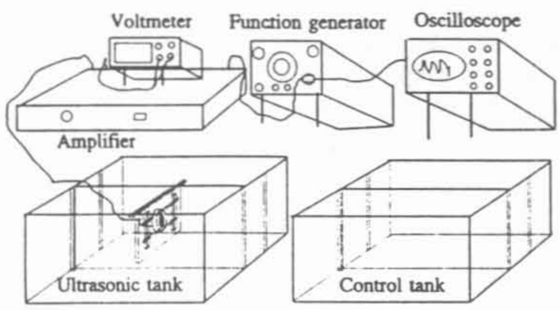

Figure 1 Experimental setup

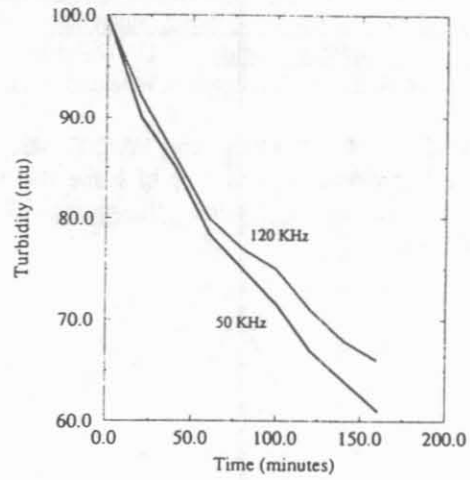

Figure 3 A comparison 50 KHz. and 120 KHz. at 10 Volts

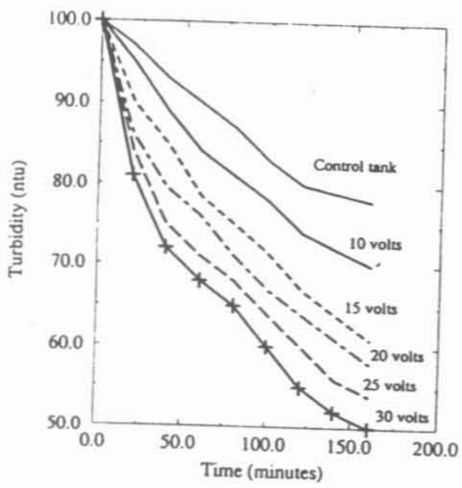

Figure 2 A comparison plot showing particle settlement at different voltages 10, 15, 20, 25, and 30 Volts, (50 Khz.)

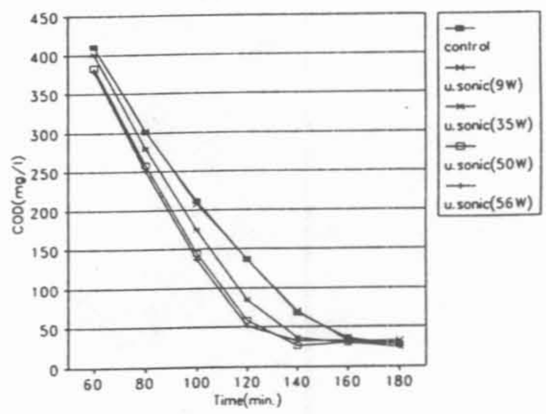

Figure 4 Chemical Oxygen Demand (COD) versus Time (60 min - 180 min) without and with Ultrasonics (50 Khz, 9 W, 35 W, 50 W, 56 W)

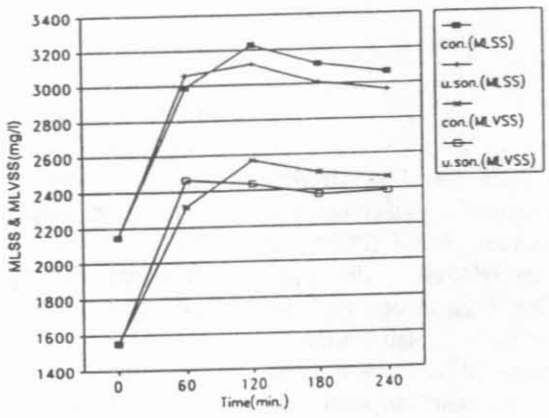

Figure 5 MLSS and MLVSS versus Time without and with Ultrasonics (50 khz, 56 W)

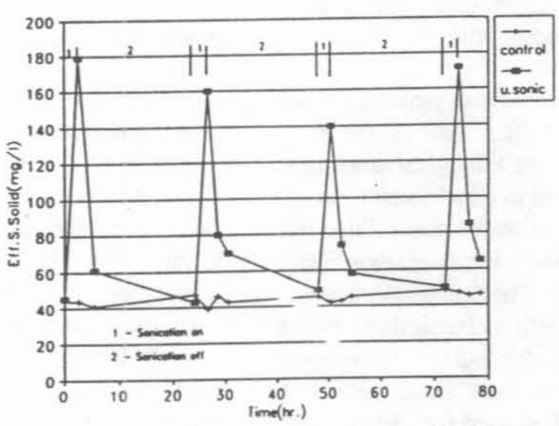

Figure 6 Effluent Suspended Solids versus Time without and with Ultrasonics (50 Khz, 50 W)