ULTRASONIC ASSISTED REMOVAL OF SUSPENDED WATER CONTAMINANTS

Krishnan Balasubramaniam, Srinivas Bolla, and Camille A. Issa
Department of Aerospace Engineering and Mechanics
Mississippi State University

INTRODUCTION

The state of Mississippi and the Gulf Coast Region have seen a significant amount of industrial and economic growth in the past decade which is expected to continue into the future. This has prompted an increase in the demand for the quantity and, more importantly, the quality of the water supply. Stiffer competition for ground and surface water sources, coupled with an increase in hazardous pollution from the expanding industries, has made the critical water quality problem more difficult to address. Improved wastewater treatment devices which are cost effective will be needed. Some of the current methods for contaminant removal from wastewater use large amounts of chemical and/or bio-organisms and often leave remnants in the water which subsequently have to be removed using a secondary treatment process.

Ultrasonic energy has found many uses in a wide range of applications: from disintegrating kidney stones to welding microchips leads, from non-invasive medical sonograms and nondestructive evaluation to underwater sonar. Ultrasonic cavitation forces in water have been documented at least forty years ago with specific needs to understand the degradation of off-shore structures and large ships. However, recent applications have pointed to using this ultrasonic forces for cleaning purposes. Much of the work accomplished thus far has been in the field of creating forces between a contaminant particle and a solid substrate.

An overall research effort is being undertaken at Mississippi State University, investigating the mechanisms of ultrasonic wastewater treatment. The initial work efforts are focused on following technical objectives:

a) To study and determine the optimal parameters for the agglomeration of unsettleable (suspension, colloids, and dissolved) particles which are commonly found in wastewater.

b) To study and demonstrate the catalytic influence of ultrasound on the growth and performance on common activated bio-organisms (sludge) already used in wastewater treatment.

c) To determine the potential for high intensity ultrasonic effect on floc settleability. Ultrasonics at high intensity can be used to assist the contaminant sedimentation and sludge removal process. This is accomplished by using the sound waves which assist the gravitational forces as well as other sedimentation techniques such as electrical chambers.

In this paper, the studies involving the effect of agglomeration of suspended particles using high intensity ultrasound (greater than 1 W/cm^2) will be discussed in detail. This approach will require the development of theoretical models to initially evaluate the optimal parameters for conducting the experiments. Initial experiments would include bench scale experiments. Based on the data collected, a prototype water cleansing pilot plant can be designed, developed, and tested.

ULTRASOUND IN ENVIRONMENTAL APPLICATIONS

In this section, a brief overview of some of the work accomplished by other researchers in the related area of cleaning using high power ultrasonics will be provided. This section demonstrates the legitimacy of the proposed concept and the relevance to industrial applications.

Extensive application of surfactant to contaminant removal cleaned oil spills from beach sands has been reported. This application then prompted attempts to remove hazardous organic chemicals from contaminated soils at Superfund sites by in situ treatment methods after Micellar-Polymer Flooding. PEI Associates conducted a systematic evaluation of surfactants and assisted by ultrasonic radiation as cleaning agents for semi-volatile organics in soils (USEPA 1988). These tests employed a synthetic soil mixture, constituted to be representative of a typical soil at a hazardous waste site. Conclusions drawn from these prior test results were that Satisfactory contaminant removal (99+%) in fine non-clay fractions (-250+10 microns) would require the imposition of significantly higher fluid-particle shear stresses than those encountered in conventional stirred tank-mixing. In this regard, fluid-particle shear stresses in the magnitude and intensity generated by ultrasonic cavitational excitation was determined to achieve satisfactory cleaning levels and at the same time minimize the need for surfactant in the cleaning process. Another paper (Coles 1990) describes an integrated soil washing system to remove semi-volatile hazardous organic chemicals (anthracene, pentachlorophenol, and dioctylphthalate) from soil (size range -20+200 mesh) using aqueous surfactant solutions (Surfactant... 1979) as the extracting medium and high mass transfer rate ultrasonic cavitational excitation for liquid-solid contacting. By using high sedimentation rate tubular or plate clarifiers for solid-liquid separations and ultrasonic cavitational excitation in extraction, equipment size requirements were reduced, making the system potentially applicable for modular transportable designs in the 100 to 300 t/d soil throughput range.

It has been found that Activated sludge microorganism activity can be enhanced using ultrasonic energy. This enhancement may be due to induced biological effects and facilitated cellular mass transfer due to ultrasonics. Ultrasonic can be destructive or constructive depending on the intensity, frequency, and exposing time. Several studies have been done to study the effects on biological cells using different types of cells (Tkachuk 1989; Bar 1988; Zabaneh and Bar 1991). A study on activated sludge microorganisms at a frequency of 2.6 MHz at intensity of 2-6 W/sq.cm. reports an enhancement of Dehydrogenase, proteolytic, and glycolytic activity by a factor of 1.9, 1.1, and 4 times, respectively (Tkachuk 1989). Other studies have been performed using different biological cells at a frequency of 20 KHz and have also observed significant enhancement of biological activity.

MECHANISM OF HIGH INTENSITY ULTRASONICS IN FLUIDS

In this section, some of the technical issues associated with the ultrasonic phenomena and various physical principles used in the proposed research will be briefly discussed.

Preliminary investigations indicate that acoustic radiation and other acoustic forces generated at modest energy levels in the 10-1000 KHz. frequency range are sufficiently strong to effectively move and concentrate suspended fine particles in aqueous systems. In this proposed separation technique, the forces causing the separation are exerted upon the suspended particles, in between the particles, and between the particles and water.

The physical mechanisms of ultrasonic interaction with materials are: (1) physical, (2) chemical, and (3) thermal. Most of the relevant mechanisms used in our research are physical in nature. Physical mechanism of ultrasound in a fluid medium can occur due to the following reasons :

(a) <u>Wave propagation</u> including standing wave patterns and Bernoulli's forces. Like all waves, 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.

(b) <u>Bubble oscillation</u> causing cavitation at high intensity levels, in the range of 0.5 to 5 watts/cm2. Micro bubbles present in a liquid grow as a result of rectified diffusion. At these levels, ultrasonics energy is known to agglomerate particles or fibers dispersed in water or liquids of similar rheological properties. Also the high strain rate associated with the high frequency wave propagation often decreases the effective viscosity and the boundary layer thickness. This in turn enhances mass, momentum, and heat transfer across boundaries.

(c) <u>Bulk effects</u> such as decrease in effective viscosity will occur. High inertia forces due to accelerations ranging from 10-100 thousand 'g' can result from a very small magnitude of the vibration, on the order of 10 microns at ultrasonic frequency. In a medium with two or three materials of various densities, the difference in the inertial forces due to ultrasonic vibration will counteract surface adhesion and enhance separation.

PRINCIPLE OF ULTRASONIC AGGLOMERATION

An important factor in the stability of unsettleable particles (suspensions, colloids as well as dissolved form) is the presence of surface charge (Zeta Potential). The charges are developed in different ways depending on the chemical composition of the waste water and the particle. Regardless, this stability can be overcome if the particles are aggregated (flocculated) into larger particles with enough mass to sediment using normal procedures. At low intensity levels of about 1 watt/cm^2, ultrasonic energy is known to agglomerate particles dispersed in water or liquids of similar rheological properties. The small particles in the fluid suspension agglomerate and the agglomerated particles are heavy enough to precipitate out of suspension under the forces of gravity and/or an applied vacuum or an electric field. One of the methods successfully shown to agglomerate suspended particle is using ultrasonic standing waves. These standing waves are caused by two intersecting out-of-phase waves (half wavelength apart). This can be accomplished using an ultrasonic transducer at one end and a reflecting plate at the other end spaced to create the phase criteria for standing wave pattern to develop (Tolt 1992).

Agglomeration is the result of forces present in an ultrasonic field. Some of these forces are orthokinetic forces (Figure 1) which depend on particle size, frequency of ultrasonic vibration, particle density, and viscosity of the fluid. These are secondary forces acting perpendicular to the direction of the sound wave propagation and causes the particles to migrate towards the antinodal points. The other primary mechanism for agglomeration is the presence Bernoulli's forces caused by the hydrodynamic flow around the suspension particles. The agglomeration process due to Bernoulli's forces could be explained by a fluid flow model between particles as shown in Figure 2. Particles of cross-sectional dimension much smaller than the wave length of ultrasound in the liquid medium and the density higher than the fluid essentially remain stationary with respect to the cyclic fluid motion as a result of the propagation of the ultrasound wave. Due to Bernoulli's effect in the constriction zone (venturi effect) between particles, the flow velocity increases and the pressure drops at the anti-nodes, resulting in an attractive force between the particles. This phenomena tends to agglomerate the particles when the attractive force due to Bernoulli's effect is higher than the repulsive force due to the similar polarity of particle surface electrical charges. The same forces cause the particles to separate (repel) at the nodes and causes the particles to travel from the high pressure nodal regions to the low pressure anti-nodal regions. The effect of frequency of the ultrasonic wave on the two mechanisms are different. At high frequencies, the ortho-kinetic forces are negligible, while the hydrodynamic forces become a major agglomerating force.

This phenomena has been experimentally demonstrated by Feke (Tote et al. 1992) using a water cell setup. A typical experiment is illustrated in Figure 3. Here, the white suspended particles are agglomerating at the anti-nodal points within a column of water using ultrasonic energy generated from a transducer at the bottom. An improvement in this standing wave method has been suggested using a drifting cell approach through frequency sweep methods to systematically move the particles to desired locations for easy separation (Benes 1991).

RECENT PROGRESS IN HIGH INTENSITY ULTRASOUND INSTRUMENTATION

The application of high intensity ultrasound to assist the industrial wastewater treatment application will require a high power ultrasonic source. Until recently, the high frequency acoustic transducers were inadequate and could not provide the requisite energy levels required for a scale up of the ultrasonic cleaning techniques to industrial requirements. Also, there is a shortfall in the availability of efficient power amplifiers which are also economical. With new advances in both these technologies, the scaling up process of ultrasound cleaning technique has become more practical. With the advent of large capacity solid-state power amplifiers using static induction transistors and static induction thyristors, output powers of 50-100 KW can be achieved (Tsujino 1989). The dimension of a 50 KW static induction thyristor power amplifier equipment are about 80 (Width) x 180 (Height) x 80 (Depth) centimeters, thus facilitating the scale up of this technology. Recent developments by several investigators, particularly Dr. Juarez (Rodriguez-Corral 1989) at the Spanish Institute of Acoustics has made significant strides using stepped plate transducers which operate at high efficiencies and transfers high power.

Such developments have prompted several other applications of ultrasonics. The most relevant is the work at Battelle, Columbus, on the separation of solid and water using high intensity ultrasonics for dewatering and drying applications (Senapathi 1989). They have successfully scaled up the dewatering process to commercial size and patented the dewatering device.

APPROACH UNDERTAKEN

The strategy for studying the agglomeration effects of high intensity ultrasound on unsettleable particles involves a combination of theoretical analysis of wave behavior in water combined with some bench scale experiments to study and select optimal parameters.

The theoretical model for ultrasonic wave in fluids is being approached by two methods. The study of acoustic wave patterns in water is analyzed by using a closed from solution for transient pressure and velocity profiles. This assumes a homogeneous fluid medium and hence cannot handle particles, but by studying the pressure variations and the velocity profiles, the hydro-dynamic forces acting on a suspended particle can be analyzed. In order to visualize the behavior of fine suspended particles, a more sophisticated numerical algorithm based on finite elements modeling is appropriate. The NASTRAN Finite Element Modeling package was chosen for this due to the availability of a Fluid-Acoustics model which can be scaled to our requirements. This model consists of a rectangular cylinder with three rigid sides and is filled with water. The fourth side is the flexible side through which the dynamic loading is applied, simulating an acoustic source. The fluid can be excited at different frequencies. The fluid portion of the model consists of either 'Hexa' or 'Penta' elements. These elements can assume the properties of irrotational and compressible fluids suitable for acoustic analysis. The mesh used to define the fluid has to have at least six elements per wavelength, in order for the results to converge.

The initial experimental efforts involve two bench scale reactors tanks, one having ultrasound generators at appropriate locations, while the other is used as a control sample. Both the tanks are maintained at identical conditions except for the ultrasound generators. The critical parameters of ultrasound such as frequency, amplitude, location of transducer, and reactor geometry is being systematically studied. Wastewater parameters such as temperature, contaminant concentration, type of contaminant, etc., can also be analyzed. A standard turbidimeter is used in the quantification of the ultrasonic removal of unsettleable particles.

SUMMARY

This research will determine the particle and ultrasonic parameters needed to achieve the energy-efficient concentration and removal of particles, especially for the purification and treatment of industrial wastewater. The ultrasonic cleaning equipment, once installed, would have a low overhead cost factor due to the relatively inexpensive operating costs. Also, very little, if any, chemicals would need to be used for cleaning the hazardous industrial wastewater. Further post processing can be avoided. Ultrasonics can also be considered a relatively safe method of cleaning. The development of such a water quality control plant are many and significant. This can also be beneficial in improving the quality of residential water supply (Safe Drinking Water Act, 1986 amendment) since industrial wastewater disposal to rivers and lakes also contaminate drinking water. Water quality affects the overall quality of life above and below the water. Hence, contaminants in industrial wastes, spent wash water from soil cleaning, etc., can potentially be better removed using an easier and more cost effective, scale up, ultrasonic assisted technique.

REFERENCES

Bar, Raphael. 1988. Ultrasound enhanced bioprocesses: cholesterol oxidation by Rhodococcus erythropolis. Biotechnology and Bioengineering. Vol 32, pp. 655-663.

Benes, E., F. Hagar, W. Bolek, and M. Groschl. Separation of dispersed particles by drifting ultrasonic resonance fields. In: Proc. of the Ultrasonics International '91 Conference. Le Touquet, France, (Butterworth-Heinemann, Oxford), 1991.

Coles, E.T., et al. Removing hazardous organics from excavated soils by ultrasonic washing. Haztech International 90, Houston Waste Conference and Exhibition, May 1990.

Rodriguez-Corral, G., et al. Developments and prospects of the stepped-plate ultrasonics power generator for use in gases. Presented at the Ultrasonic International '89 Conference. Madrid, Spain, 1989. (Elseiver Press, Netherlands).

Semapathi, N. Scaling up of ultrasonically enhanced process. Ultrasonics International, 1989, Conference Proceedings. (Elseiver Press, Netherlands), pp. 236-243.

Surfactant and detersive system. In: Kirk-Othmer Encyclopedia of Chemical Technology, 3rd Edition. volume 22. John Wiley and Sons, New York, 1979, pp 332-432.

Tkachuk, N. G., V. V. Kravets, and G. A. Nikitin. 1989. Intensification of the activity of activated sludge microorganisms with ultrasound. Soviet Journal of Water Chemistry and Technology. VII, n 6.

Tolt, T.L. and D.L. Feke. Separation devices based on forced coincidence response of fluid-filled pipes. J. Acoust. Soc. of Am. 91 (6), June 1992, pp. 3152-3156.

Tsujino, J. A review of new industrial applications of high power ultrasonics in Japan. Presented at the Ultrasonic International '89 conference. Madrid, Spain, 1989, (Elseiver Press, Netherlands), pp. 346-353.

USEPA. 1988. CERCLA BOAT SARM preparation results of physical soils washing experiments. EPA Contract No. 68-03-3413. Hazardous Waste Engineering Research Laboratory. U.S. Environmental Protection Agency. Cincinnati, Ohio.

Zabaneh, Munder and Raphael Bar. 1991. Ultrasound enhanced bioprocesses II: Dehydrogenation of hydrocortisone by arthrobacter simplex. Biotechnology and Bioengineering. Vol 37, pp. 998-1003.

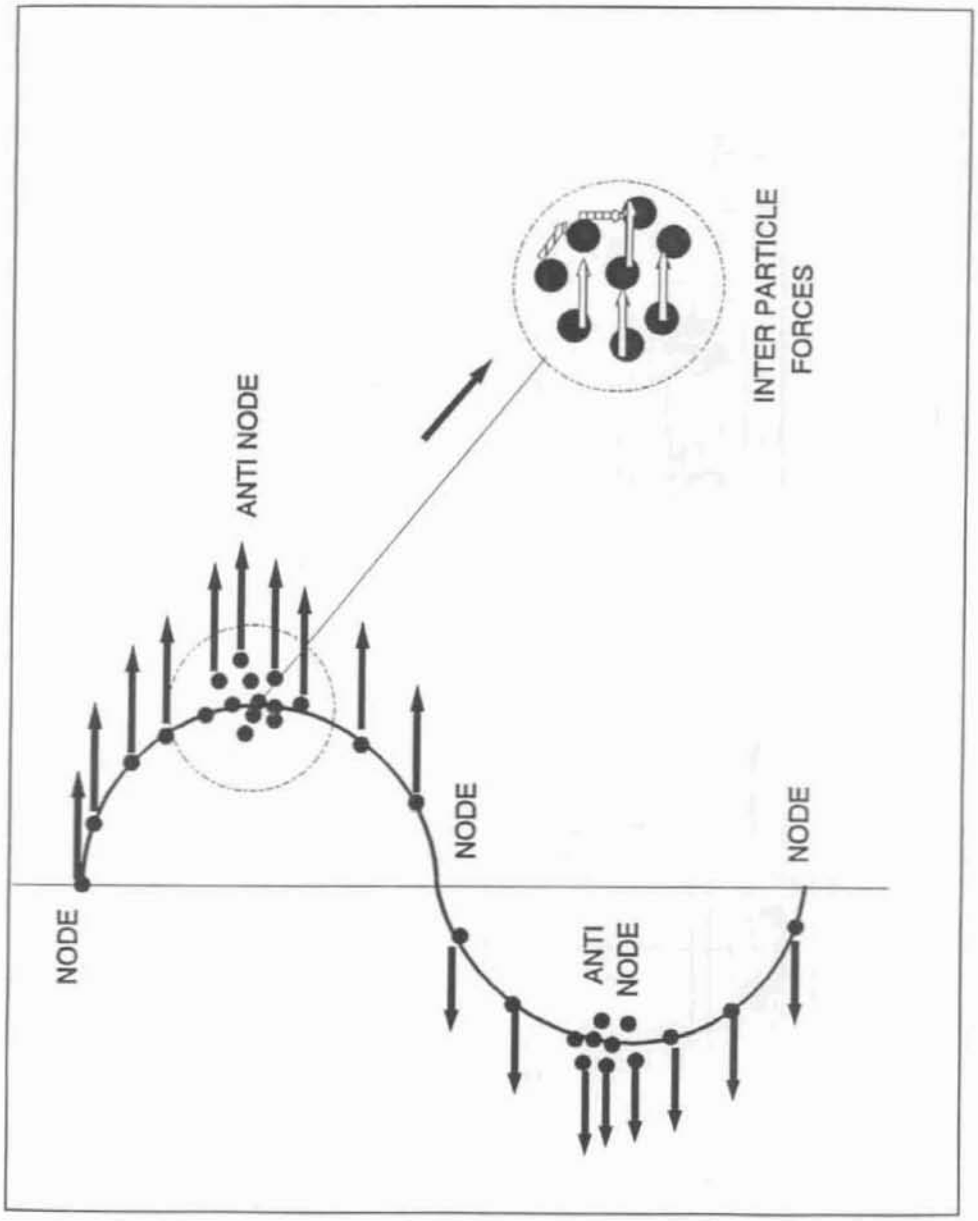

Figure 1. The ortho-kinetic mechanism of migration of particles to the antinodal regions.

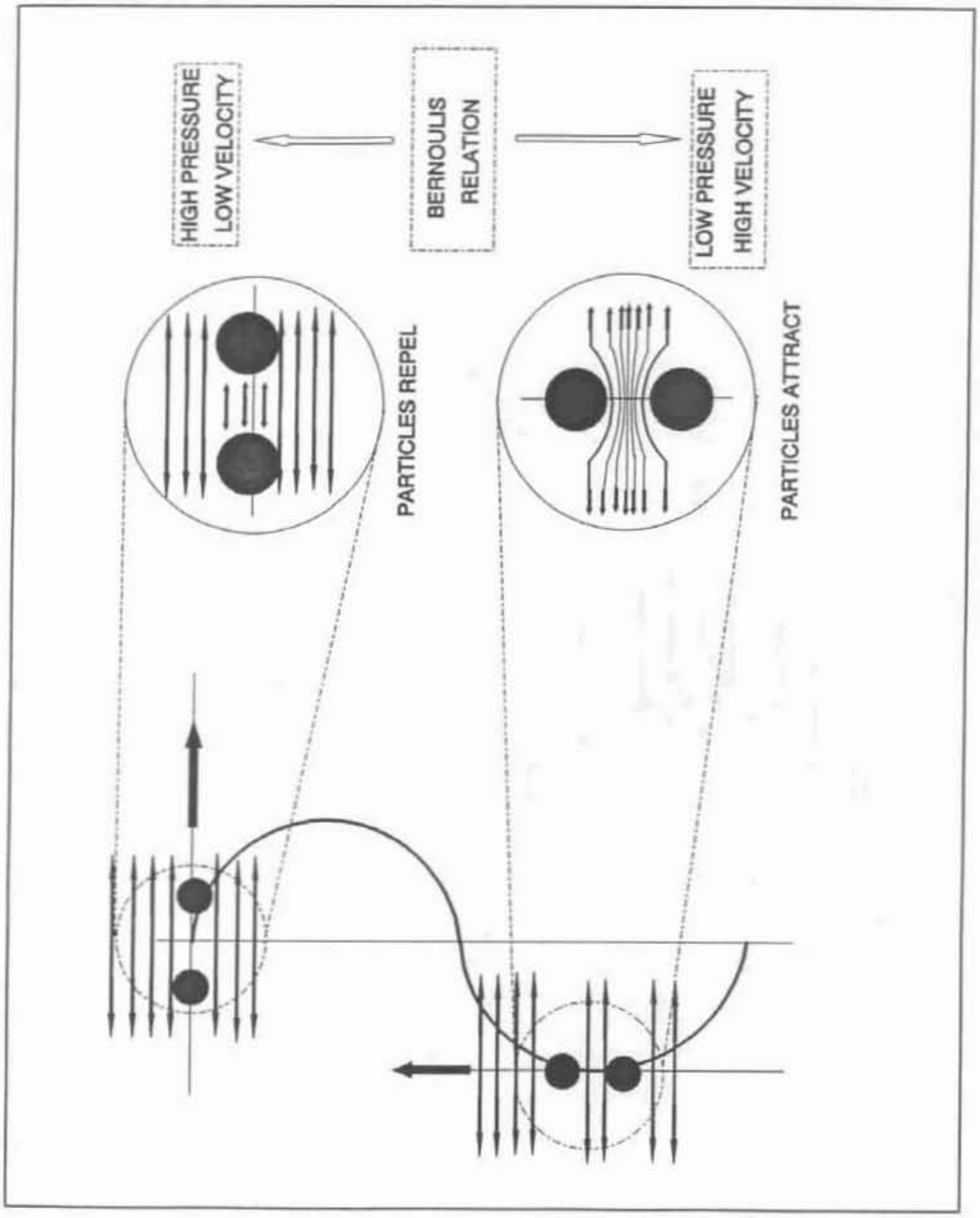

Figure 2. The hydro-dynamic forces which cause attraction at anti-nodes and repulsion at nodes using Bernoulli's forces. This pressure difference between the nodes and the antinodes cause particle migration to anti-node regions.

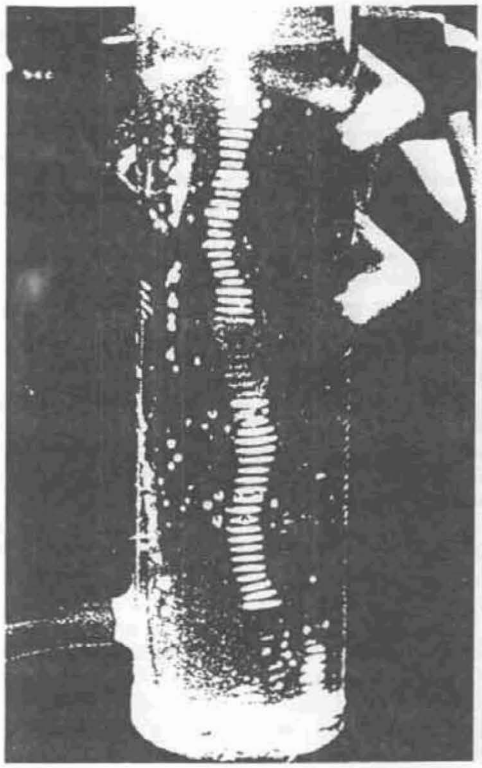

Figure 3. Experimental demonstration of agglomeration of 80 micron alumina particles spaced by a distance equal to the half-wavelength in the water in a 2.5 cm diameter, 12.7 cm long glass tube cell driven by a single ultrasound transducer located at the bottom.