Project # 55179
Renewed as 73896

INTERIM REPORT
U.S. Department of Energy

Acoustic Probe for Solid-Gas-Liquid Suspension

Principle Investigator: Dr. L.L. Tavlarides
Co-Principle Investigator: Dr. Ashok Sangani
Institution: Syracuse University

Collaborators: Dr. P. Spelt[+]
Dr. M.A. Norato[+]
Dr. M. Greenwood[*]
Mr. M. Hedges[+]
Institutions: Syracuse University[+]
Pacific Northwest National Laboratory*

Grant Number: DE-FG07-96-ER14729
Grant Project Officers: Dr. Oscar P. Manley
(Review and Evaluation of Research)
Dr. Gordon Roesler Massey
(Review and Evaluation of Application of Research)
Project Duration: First Funding Period 9-15-96 to 9-14-2000
Second Funding Period 9-15-2000 to 9-14-2003

Table of Contents

3. Executive Summary 1

4. Research and Objectives 2

5. Methods and Results 3

6. Relevance, Impact and Technology Transfer 9

7. Project Productivity 14

8. Personnel Supported 14

9. Publications 14

10. Interactions 15

11. Transitions 16

12. Patents 16

13. Future Work 18

14. Literature Cited 16

15. Feedback 17

16. Appendices 17

17. Quantities/Packaging .....

3. Executive Summary

The main objective of the project during the first period of funding is to develop an acoustic probe for monitoring particle size and volume fraction in slurries in the absence and presence of gas bubbles. The goals are to commission and verify the probe components and system operation, develop theory for the forward and inverse problems for acoustic wave propagation through a three phase medium, and experimentally verify the theoretical analysis. The acoustic probe will permit measurement of solid content in gas-liquid-solid waste slurries in tanks and pipelines across the Department of Energy complex. Particularly, in the second funding period, a prototype probe will be fabricated, commissioned and tested to demonstrate the capability to accurately measure slurries of one to five weight percent solids.

Our research work has established a solid theoretical foundation for predicting attenuation and phase speed of acoustic waves propagating through solid-liquid suspensions, both in the presence as well as absence of gas bubbles. The theory is based on ensemble averaging of the equations of motion in the solid and liquid phases to obtain expressions for the "effective properties" of the slurry mixture in terms of coefficients which appear in the equations of motion for the solid particle. The attenuation theory accounts for losses due to viscous dissipation, nonadiabatic thermal effects, and incoherent scattering, and as a result can cover a wide range of frequencies and particle sizes. The theory also applies to polydispersed suspensions of spherical particles. The theory agrees with results obtained by previous investigations who examined limiting cases of thermal attenuation at small volume fraction (Allegra and Hawley, 1972) and viscous attenuation at large frequencies (Sangani, Zhang and Prosperetti, 1991). The comprehensive theory developed allows us to interrogate a relatively large range of particle sizes and physical properties. The attenuations predicted from theory are in generally good agreement with experimental data obtained by Pulse/FFT data acquisition methods for solid-liquid slurries of soda-lime glass particles of 14.9 microns and 65 microns mean radius and polystyene particles of 79 microns mean radius at concentrations ranging from 5 to 50 percent solids by volume in water. The primary attenuation mechanisms for the former system are due to viscous and scattering losses, whereas, for the latter system, thermal and scattering losses dominate. Good comparisons are also obtained for 0.11 micron radius polystyrene particles in water from 5 to 50 percent solids by volume (Allegra and Hawley, 1992) where attenuation is dominated by thermal affects.

Another goal of the project was to devise a technique to remove the noise introduced by the presence of a small amount of gas bubbles in the suspension to infer the properties of the solid-liquid suspension. Experiments and analyses were made for the solid-gas-liquid slurries of soda lime glass particles of 14.9 micron mean radius at 5 and 10 percent by volume in water with gas bubbles from 25 to 150 micron radius at low volume fractions. The primary conclusion is that the noise is significant at low frequencies near the bubble resonance frequencies and the noise is minimal at high frequencies. We show it is possible to estimate the effects of bubbles and eliminate the slight noise produced by bubbles at higher frequencies to yield the volume fraction of the particles.

An inverse theory was also developed to determine the concentration and solids particle size distribution in a solid-liquid slurry given the attenuation as a function of frequency using regularization techniques that have been successful for bubbly liquids. We have found that the success of solving the inverse problem is limited since it depends strongly on the physical properties of the particles and the frequency range used in the inverse calculations. We have determined bounds necessary for determining the particle size distribution.

The first six months of the new funding period focused on demonstrating the capability to accurately measure volume fractions of dilute suspensions in the range of 0.004 to 0.050 percent. The Pulse/FFT method accurately measures attenuation for soda lime glass beads (14.9 micron radius), clays in water, and a Hanford surrogate salt simulant in this range. A linear relationship is obtained for attenuation versus volume fraction, and the theory accurately predicts the monodispersed soda-lime glass bead data. The linear relationship should readily permit application of the acoustic monitor to dilute slurries.

The results of this project has relevance to the DOE mission of mobilizing, transporting and processing solid-liquid slurries by providing a reliable and safe monitor of percent solids in these slurries. Significant impact is expected for application as an accurate, safe and reliable monitor which is non-invasive is required to quantify across site transfer of dilute and concentrated slurries from storage tanks to processing facilities for high level waste treatment. Transfer of this technology to the DOE complex is the primary objective of the second funding period of this project whereby a proto-type acoustic monitor will be designed, commissioned and demonstrated to accurately measure low weight percent slurries in a flow loop and on a test transfer line.

4. Research Objectives

The primary objective of the research project during the first funding period was to develop an acoustic probe to measure volume percent solids in solid-liquid slurries in the presence of small amounts of gas bubbles. This problem was addressed because of the great need for a non-invasive, accurate and reliable method for solids monitoring in liquid slurries in the presence of radiolytically generated gases throughout the DOE complex. These measurements are necessary during mobilization of salts and sediments in tanks, transport of these slurries in transfer lines to processing facilities across a site, and, in some instances, during high level waste processing. Although acoustic probes have been commonly used for monitoring flows in single-phase fluids (McLeod, 1967), their application to monitor two-phase mixtures has not yet fully realized its potential. A number of investigators in recent years have therefore been involved in developing probes for measuring the volume fractions in liquid solid suspensions (Atkinson and Kytomaa, 1993; Greenwood et al., 1993; Martin et al., 1995) and in liquid-liquid suspensions (Bonnet and Tavlarides, 1987; Tavlarides and Bonnet, 1988, Yi and Tavlarides, 1990; Tsouris and Tavlarides, 1993, Tsouris et al., 1995). In particular, Atkinson and Kytomaa (1993) showed that the acoustic technique can be used to determine both the velocity and the volume fraction of solids while Martin et al. (1995) and Spelt et al. (1999) showed that the acoustic probe can also be used to obtain information on the size distribution of the particles. In a recent testing of in-line slurry monitors with radioactive slurries suspended with Pulsair Mixers (Hylton & Bayne, 1999), an acoustic probe did not compare well with other instruments most

probably due to presence of entrained gases and improper acoustic frequency range of interrogation.

The work of the investigators cited has established the potential of the acoustic probe for characterizing/monitoring two-phase flows in relatively ideal, well-characterized suspensions. Two major factors which we judge has prevented its wide-spread use in the processing industry, particularly for dilute suspensions, is careful selection of the frequency range for interrogation and quantification and removal of the noise introduced by bubbles from the acoustic signal obtained from the suspension.

Our research during the first funding period to develop an acoustic probe for solid-gas-liquid suspensions has resulted in a theory, supported by our experiments, to describe small-amplitude dilute suspensions (Norato, 1999, Spelt et al., 1999, Spelt et al., 2001). The theory agrees well with experimental data of sound attenuation up to 45 vol % suspensions of 0.11 and 77 micron radius polystyrene particles in water and 0.4 to 40 vol %, suspensions of 32 micron soda-lime glass particles in water. Also, analyses of our attenuation experiments for solid-gas-liquid experiments suggest the theory can be applied to correct for signal interference due to the presence of bubbles over a selected frequency range to permit determination of the solid-liquid volume fraction. Further, we show experimentally that a reliable linear dependency of weight percent solids with attenuation is obtained for low weight fractions at high frequencies of interrogation where bubble interference is minimal.

There was a collaborative effort during the first funding period with the Pacific Northwest National Laboratories in that Dr. Margaret Greenwood was a co-investigator on the project. Dr. Greenwood provided a high level of experimental knowledge and techniques on ultrasound propagation, measurement and data processing. During the second funding period the slurry test loop at Oak Ridge National Laboratories under the direction of Mr. Tom Hylton will be employed to demonstrate the measurement capabilities of the proto-type acoustic monitor.

5. Methods and Results

Our research during the last three and one-half years has established a solid theoretical foundation for predicting attenuation and phase speed of acoustic waves propagating through solid-liquid suspensions, both in the presence as well as absence of gas bubbles (Spelt et al., 1998; Spelt et al., 2001). The attenuation theory accounts for losses due to viscous dissipation, nonadiabatic thermal effects, and incoherent scattering, and as a result can cover a wide range of frequencies and particle sizes. The theory also applies to polydisperse suspensions of spherical particles. The theory agrees with the results obtained by previous investigators who examined limiting cases. For example, our theory agrees with that of Allegra and Hawley (1972) who considered only the case of thermal attenuation at small volume fractions and with Sangani, Zhang and Proseperetti (1991) who considered only the case of viscous attenuation at large frequencies. The comprehensive theory developed allows us to interrogate a relatively large range of particle sizes or particle physical properties. The theory was also tested against the experimental data obtained by previous investigators (e.g. (Allegra and Hawley, 1972)) and in our laboratory.

Demonstration of our theory is accomplished experimentally with the set-up shown in Figure 1. An ultrasonic pulse generator (Panametrics 5052 PR) generates an electric pulse and sends it to the emitting transducer. The actuated emitting transducer transmits an acoustic pulse through the sample actuating the receiving transducer, where the signal is transmitted to and read by an oscilloscope (Lecroy 9310A). An FFT analysis of the amplitude is performed on the spike pulse, outputting voltage as a function of frequencies of the pulse. This procedure is performed on the suspending liquid, and the solid-liquid or solid-gas bubble-liquid slurry. The voltages are used to calculate attenuation.

Comparison between the theory and the experiments is shown in Figures 2-6. Figure 2 shows attenuation as a function of frequency for glass particles with about 15 micron radius at 5 and 10 percent volume fractions. For these particles the viscous and scattering losses are the primary attenuation mechanisms for the range of frequency considered in the figure. Figure 3 shows the comparison for about 77 micron radius polystyrene particles in water at 5 percent volume fractions. For this system the thermal attenuation is important at smaller frequencies and scattering at higher frequencies. The two theoretical curves correspond to assuming that (i) the suspension is monodisperse and (ii) the particle size distribution is Gaussian with a standard deviation of 1 micron. The peaks seen in the figure correspond to resonances in shape oscillations. Figure 4 shows attenuation as a function of volume fraction for 63 micron glass particles in water at various frequencies. The viscous and scattering losses are important in these relatively dense suspensions. Good agreement here suggests that the theory is reasonably accurate in predicting the volume fraction dependence even at high volume fractions. Figure 5 shows comparison with the data for 0.11 micron polystyrene particles in water obtained by Allegra and Hawley (1972). For this system the attenuation is dominated by the thermal effects.

In Spelt et al. (1999) we investigated in detail the inverse problem so determining the particle size distribution of the particles given the attenuation as a function of frequency. We devised and compared various analytical techniques for solving the inverse problem and determined the conditions, e.g. the particle size and frequency range, necessary for determining the particle size distribution.

As mentioned earlier, one of the aims of our project was to devise a technique whereby the noise introduced by the presence of small amount of gas bubbles in the suspension can be removed to infer the properties of solid-liquid suspension. We have done detailed analysis of the noise introduced by bubbles. The primary conclusion is that the noise is significant at frequencies that are not much greater than the resonance frequencies of bubbles. Beyond the resonance frequency of the bubbles, the attenuation due to the presence of bubbles decrease with the increasing frequency while the attenuation due to solids increase with the increasing frequency. Thus the noise is minimal at sufficiently high frequencies. It is possible then to use the data at low frequencies to estimate the effects of bubbles and eliminate the slight noise produced by the bubbles at higher frequencies to yield volume fraction of the particles. We have illustrated this through our experiments on solid-liquid suspensions sparged with bubbles. The

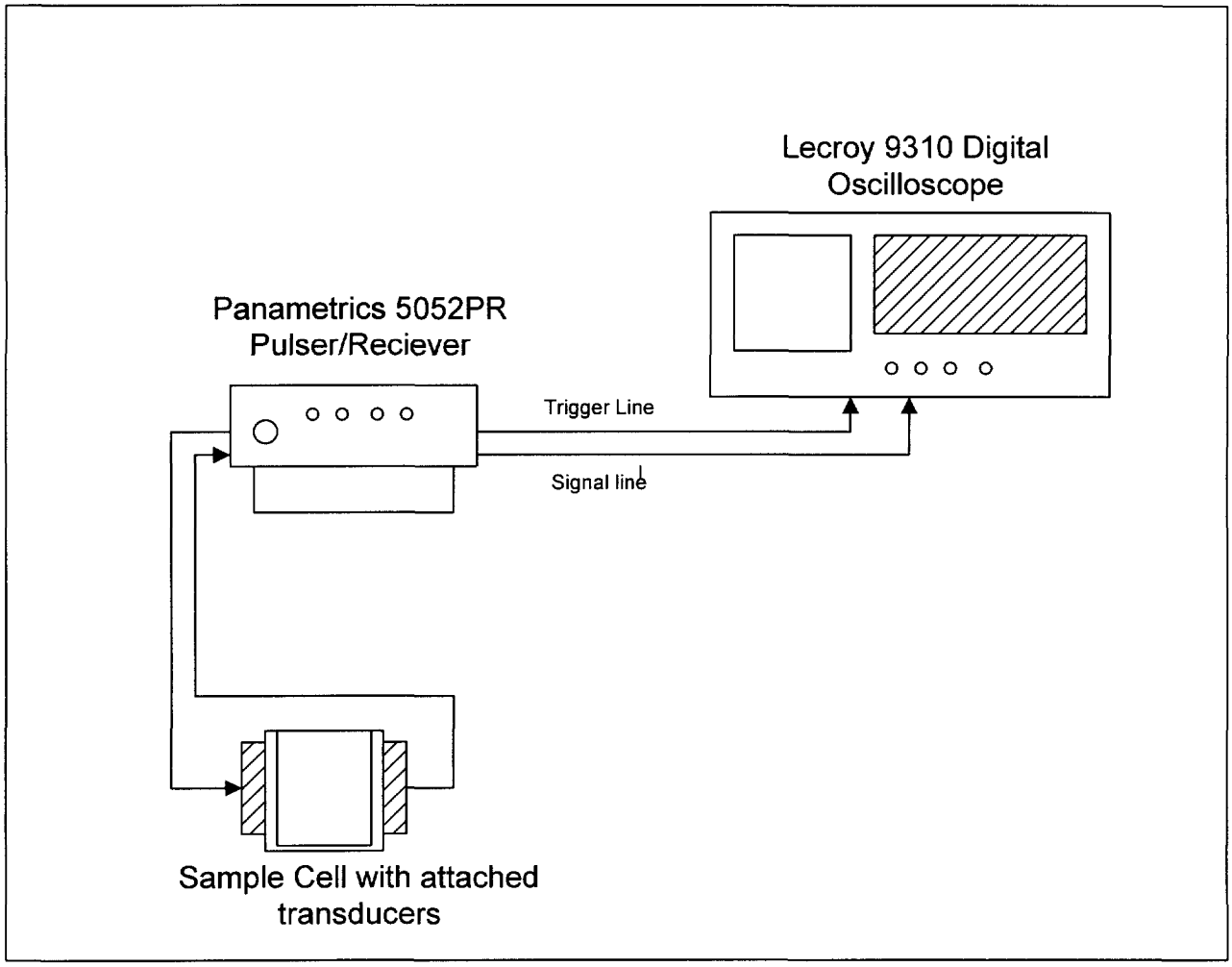

Figure 1. Schematic diagram of Pulse/FFT setup used to measure attenuation. A spike pulse is generated by the pulser/receiver and is transmitted to the transmitting transducer which is in contact with the sample. After traveling through the sample and being acquired by the receiving transducer the pulse is routed through the pulser/receiver to the oscilloscope.

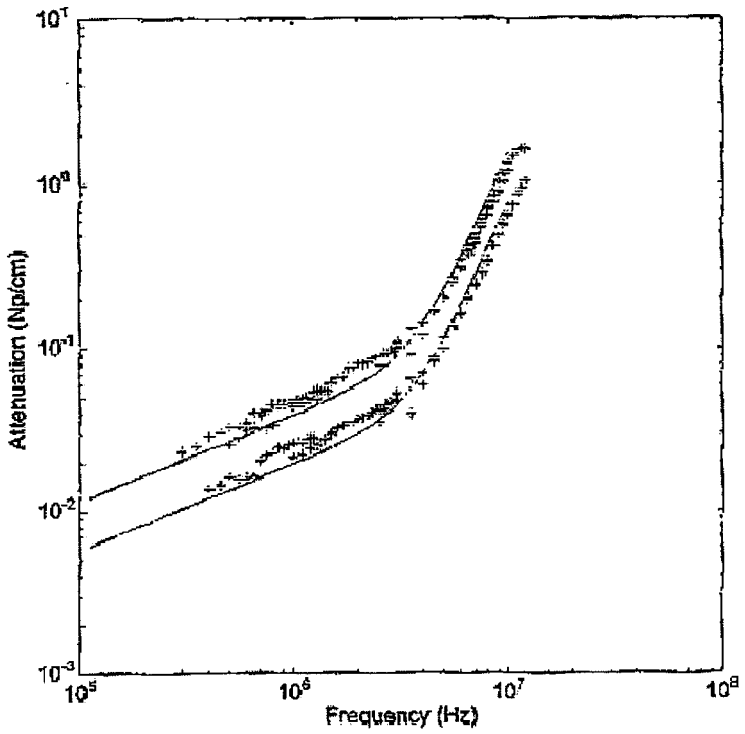

Figure 2. Comparison between experimental results and forward problem theory predictions for the attenuation versus frequency curves for soda-lime glass slurries at 5% and 10% solids by volume. The experimental solids size distribution has a mean radius of 14.9 microns with standard deviation of 3.56 microns. The forward theory predictions are based on a log-normal distribution with a mean radius of 14 microns and standard deviation of 7 microns.

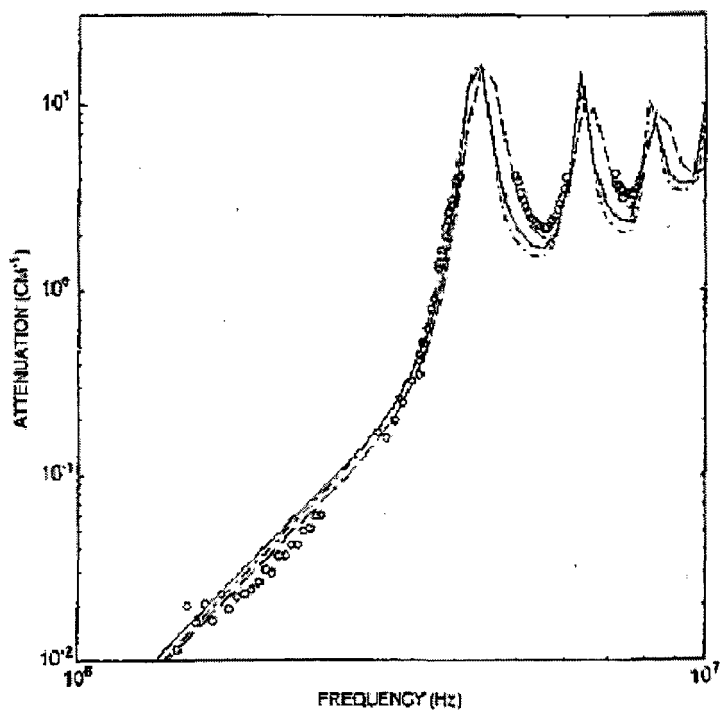

Figure 3. Experimental and theoretical results for the attenuation in a mixture of polystyrene particles (mean radius 79 ± 3 micron and 1.8 micron standard deviation) in water at 0.05 volume fraction. Circles are experiments, solid and broken lines are the theory for monodispersed particles of 79 microns and 77 microns radius, respectively.

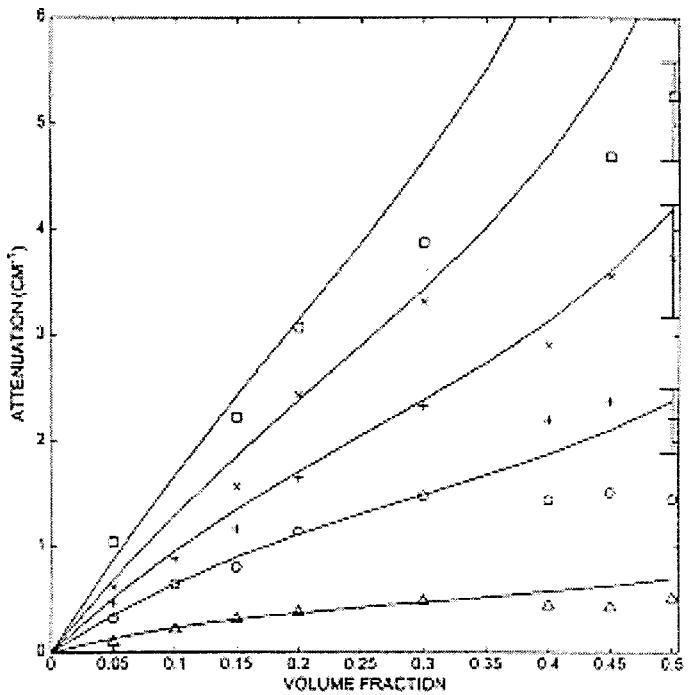

Figure 4. Experimental and theoretical results for the attenuation as a function of volume fraction for different frequencies, using glass particles (63 ± 8.5 microns radius) and glycerol. Markers: experiments, and solid lines: theory for monodispersed particles. Frequencies: 2.5 MHz (Δ); 3.5 MHz (o); 4 MHz (+); 4.5 MHz (x); 5 MHz (□).

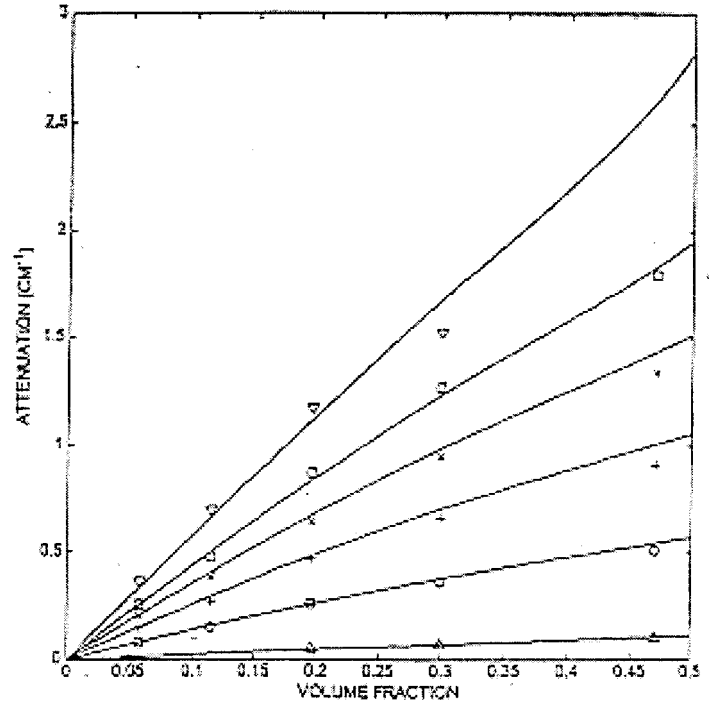

Figure 5. Attenuation as a function of solids volume fraction for the data of Allegra and Hawley (1972). The symbols represent experimental data at 3 MHz (Δ); 9 MHz (o); 15 MHz (+); 21 MHz (x); 39 MHz (∇). The curves represent the results of the effective medium approach used in this study.

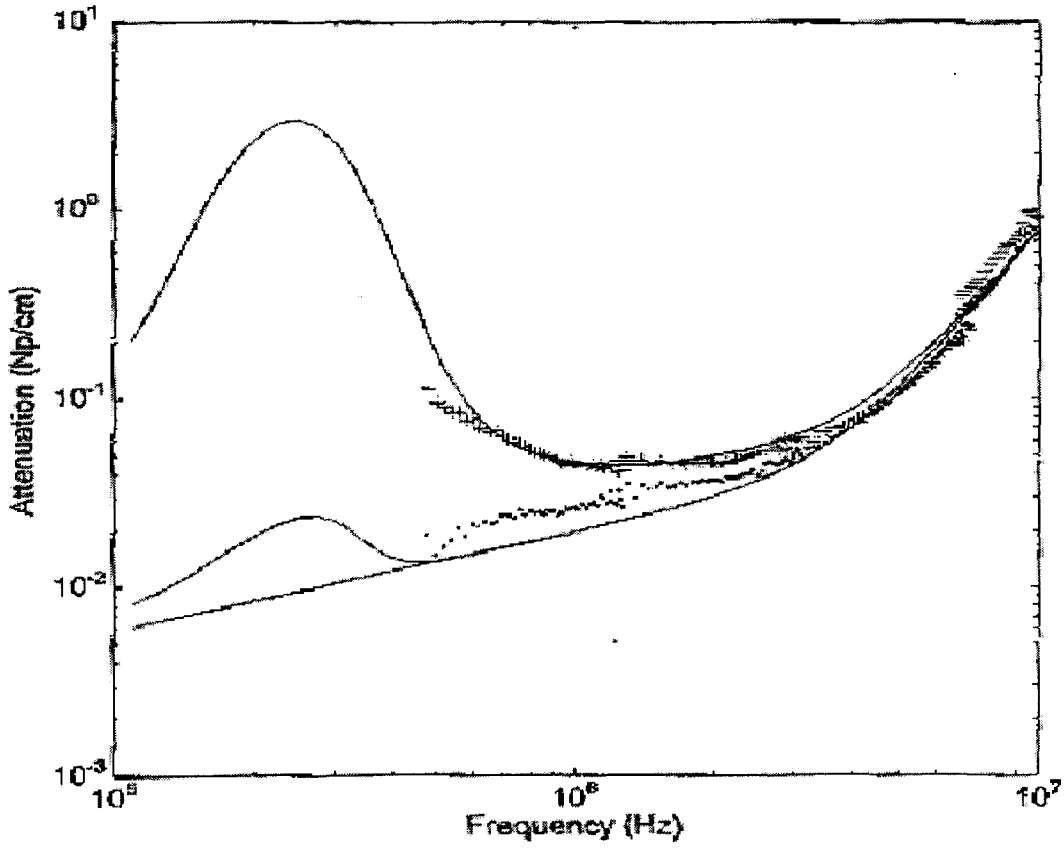

Figure 6. Results of predicting the attenuation due to the presence of bubbles in a solid-gas-liquid slurry and simply subtracting that attenuation from the total attenuation. The symbols represent experimental data for the solid-liquid and solid-gas-liquid slurries and the difference after subtracting the bubble attenuation.

preliminary results have been presented in the PhD dissertation of the student supported by the research (Norato, 1999); a more complete work will be submitted for publication in the near future. Figure 6 shows a comparison between theory and experiments for a gas-solid-liquid system. Note that the attenuation as a function of frequency goes through a minimum as the attenuation due to bubbles diminish while that due to solids increase with increasing frequency.

The above mentioned work deals with solids weight fraction above 5 percent. Our current activities extend the method to dilute suspensions in the weight percent range of 1-5 percent. We have conducted experiments for these low weight percents. The results are shown in Figures 7-9. We note from Figure 7 that the experimental data for soda-lime glass beads are in a reasonably good agreement with the theory based on monodispersed suspensions with no adjustable parameters. Figures 8 and 9 show that attenuation is significant for the entire range of volume fractions. Figure 9 shows results for a crystallized salt solution prepared according to surrogate protocol procedures for average Hanford supernate containing suspended salt particles (Glocar et al., 2000). These results show that with suitable calibration of the particle size, it would be possible to determine the volume fraction of particles from such attenuation frequency data. In principle only one calibration point would be needed, as a linear relationship appears to hold.

6. Relevance, Impact and Technology Transfer

The following answers the nine questions posed for this section.

a. This scientific work has direct application to monitor, in real time, solid-liquid slurry suspensions in the presence of gas bubbles at volume fractions of solids from 0.005 to 0.50. Monitors can potentially be installed both on transfer lines, in a non-invasive manner, or in-tanks through riser entry ports.

b. This new technology has the potential to improve cleanup approaches and significantly reduce future costs, schedules and risks and meet DOE compliance requirements in the following ways:

b.1) By assuring uniform suspensions of solids through a tank during mobilization, sluicing, or emptying of tank salts and sediments. Time and costs to execute these operations will be minimized.

b.2) Transfer of low weight percent slurries in transfer lines from DOE operated tank farms to a contractor staging tanks for processing can be done in an accurate manner. This assurance will permit compliance of schedule requirements and appropriate guarantee of required and expected material transfers.

b.3) The monitor can be employed to determine onset of transfer line plugging to prevent such occurrences and alert personnel for quick and appropriate response

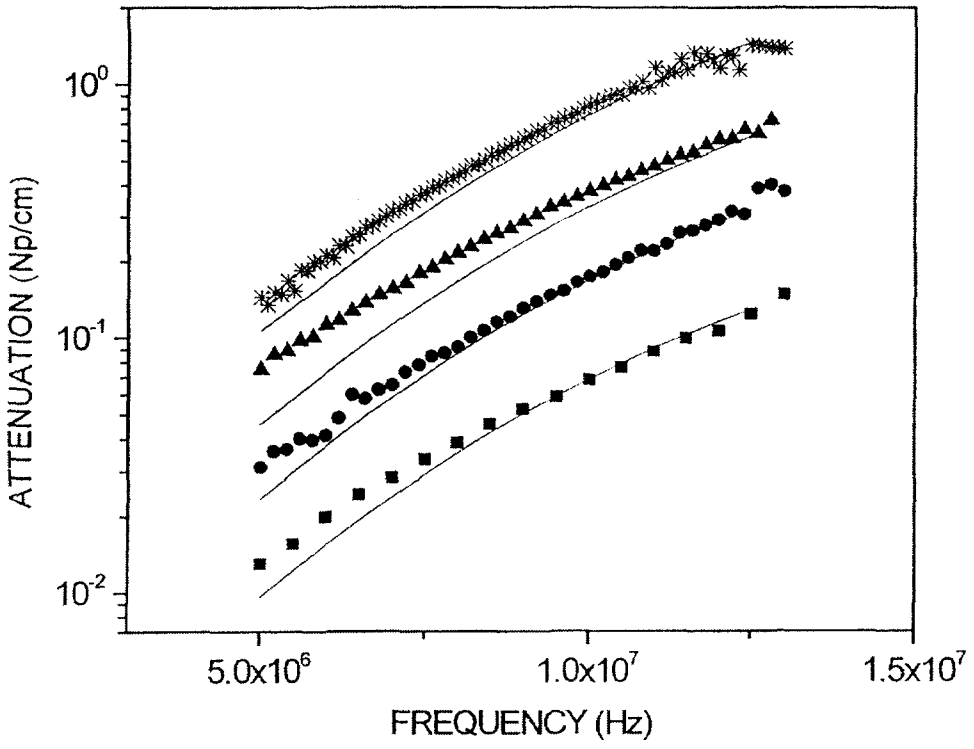

Figure 7. Attenuation versus frequency for slurries of 15 micron glass particles in water at various weight percent solids. The comparisons of theory (solid lines) with experiments (symbols) are given in ascending order for 1.0, 2.5, 5.0 and 12.0 weight percent solids.

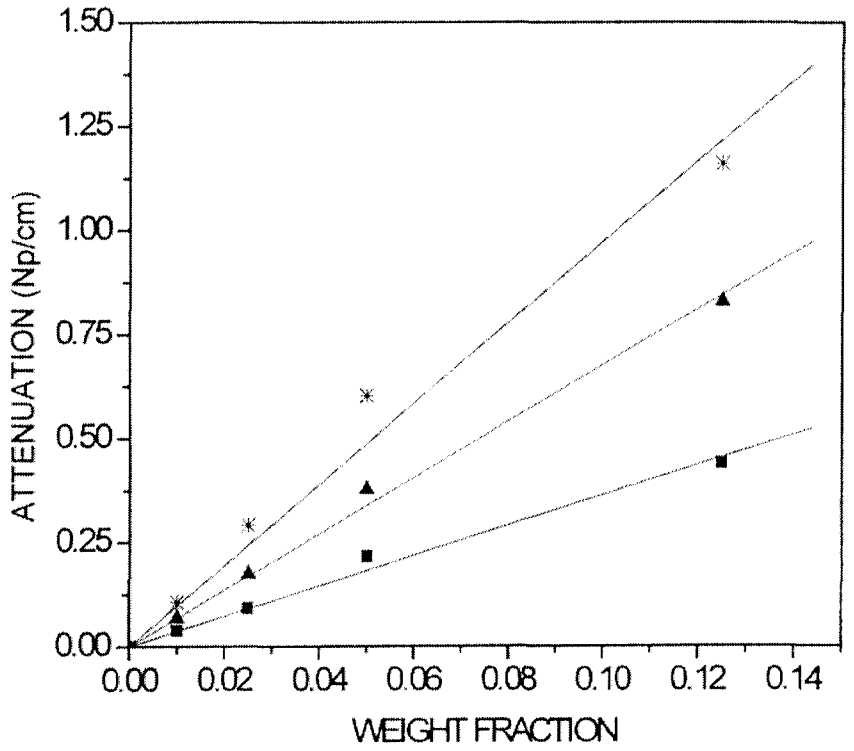

Figure 8. Attenuation versus weight fraction for slurries of 16 micron glass particles in water at three frequencies. Data shown with symbols are compared with a linear fit shown as solid lines. The curves in ascending order are for frequencies of 8, 10, and 12 MHz.

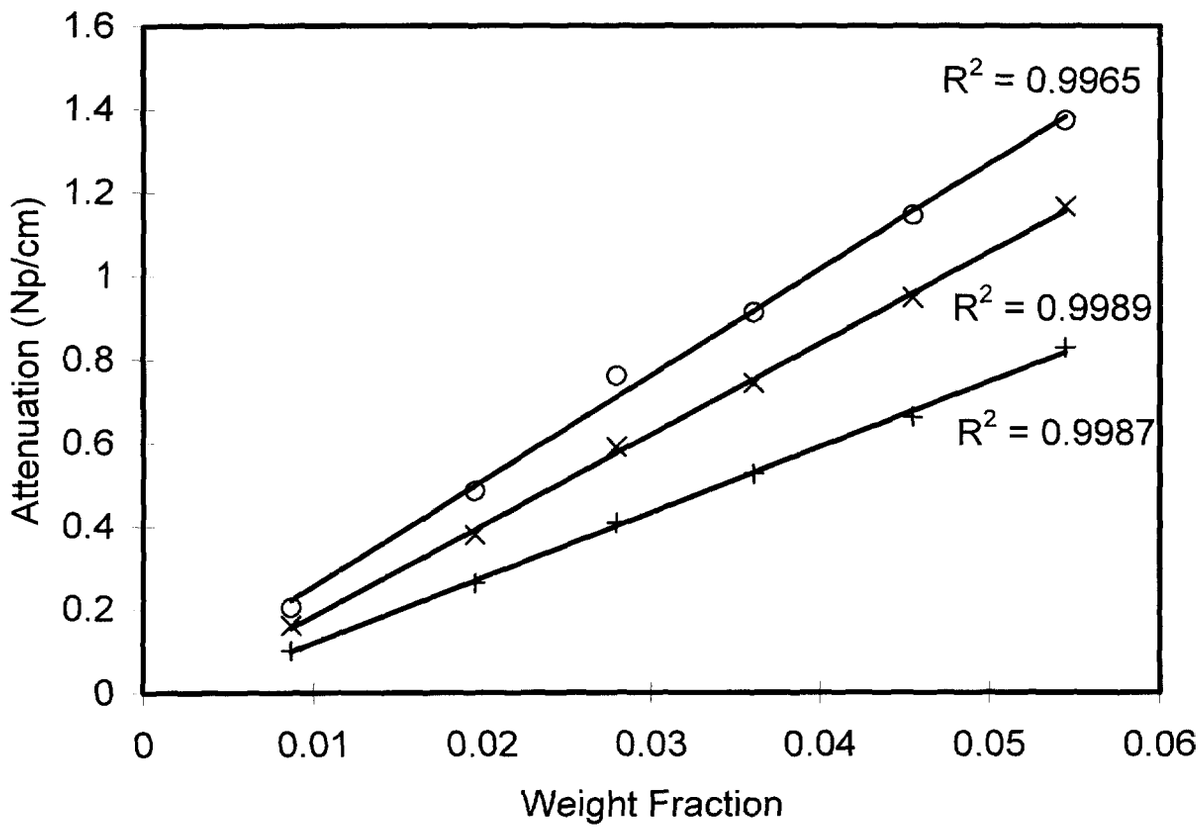

Figure 9 Attenuation versus weight fraction for the crystallized salt solution at three frequencies. The frequencies studied are (o) 12 MHz (x), 10 MHz, and (+) 8 MHz.

b.4) The monitor can be used to assure homogeneous suspensions of a mixture of solids in processing vessels during HLW and LAW treatment, for example, to guarantee glass former slurries uniformity for feeding melters.

c. The continuation of the project during the second funding period will result in a proto-type monitor which will be demonstrated at the ORNL flow loop. Also, efforts will be made to test it at the Hanford site. This effort should be completed by 9-30-03. Rapid deployment could follow subsequently pending success and availability of funds.

d. The project impact at Syracuse University resulted in continuation of this scientific effort leading to the proto-type development. The University infrastructure to conduct this research has improved through equipment acquisition and laboratory development. We have graduated one PhD, one MS and trained during the first funding period. We have had a collaboration with Dr. Margaret Greenwood from PNNL during the first funding period and a two-way transfer of knowledge was accomplished. We have an agreement with ORNL to test the prototype monitor on the ORNL two phase flow loop during the second funding period, and this should provide a quality test facility and personnel for this aspect of the project. See section c above for answers to the remaining questions.

e. Larger scale proto-type monitor development and testing are warranted, required and in progress with the second funding period of this project. The knowledge attained during the first period of funding is the basis for the proto-type monitor development and expected success in demonstration and future deployment.

f. Our collaboration with PNNL scientist Dr. Margaret Greenwood resulted in training Dr. Michael Norato (during his Ph.D. thesis work on the project) and transfer of knowledge. Our subsequent improvements of the monitor using the Pulse/FFT provides another technique PNNL can employ for their acoustic ultrasound investigations. Our particle size measurement and estimation techniques from attenuation measurements also should be of benefit to PNNL activities in this application.

g. We have increased out understanding in this area by improving our knowledge to monitor (experimental developments) and interpret attenuation signals (theoretical developments) heretofore not as accurately possible. These results provide the basis for continued development of the acoustic monitor.

h. The hurdles to overcome are the topics of the current funding period. These include:

h.1) Development of software and data acquisition system to determine volume fraction of particles.

h.2) Construct, test and commission in-line/at-tank acoustic monitor.

h.3) Conduct flow loop tests of monitor at ORNL and refine as needed.

h.4) Test refined monitor at Hanford.

i. Ms. Judith Ann Bamberger (509-375-3898-FON; Judith.bamberger@pnl.gov) offered to collaborate on the project. Should we have success on h.3 above she offered to assist in implementation/testing at a Hanford test loop. Dr. Rajiv Srivastava, Florida International University, also offered to collaborate in ways yet to be determined.

7. Project Productivity

The project accomplished most of the targeted goals. We requested and received a one-year no cost extension on the project due to typical delays in progress. We were not able to develop a theory to invert the acoustic signal to permit unambiguous prediction of the solid particle size distribution, along with the volume fraction. We show regions of physical properties and signal interrogation ranges where this may be possible. The results we have obtained were, however, quite valuable and are the basis for the continuation as described above.

8. Personnel supported:

8.1. P.I. Prof. Lawrence L. Tavlarides, Syracuse University
Co-P.I.: Professor Ashok Sangani, Syracuse, University
Co-Investigator: Dr. Margaret Greenwood
Post-Doctoral: Dr. Peter Spelt, currently at Imperial College, London, UK
Ph.D. Student: Dr. Michael A. Norato, currently at Westinghouse SRTC
M.S. Student: Mr. Mark Hedges, currently at Kionex, Inc.
Research Associate: Mr. Alexander Shcherbakov, on leave N.T.U. Kiev, Ukraine

9. Publications

9.1 Noratok, M.A., "Acoustic Probe for the Characterization of Solid-Gas-Liquid Slurries," Ph.D. Thesis, Syracuse University, May 1999.

9.2 Hedges, M., "Ultrasound Characterization of Low Volume Fraction Solid-Liquid Slurries," M.S. Thesis, Syracuse University, January 2001.

9.3 Spelt, P.D.M., Norato, M.A., Sangani, A.S., and Tavlarides, L.L., "Determination of Particle Size Distributions from Acoustic Wave Propagation," Physics of Fluids, Vol. 11 ns, 1065-1080 (1999).

9.4 Spelt, P.D.M., Norato, M.A., Sangani, A.S., Greenwood, M.S., and Tavlarides, L.L., "Attenuation of Sound in Concentrated Suspensions: Theory and Experiments," Jl. of Fluid Mechanics, 420, 1-36 (2001).

9.5 In preparation from Norato's Thesis.

9.6 In preparation from Hedges' Thesis.

10. Interactions

10.1 M. Norato, P. Spelt, A. Sangani, M. Greenwood, L.L Tavlarides, "An Acoustic Probe for the Characterization of Three-Phase Slurries," 1997 Annual AIChE Meeting, Los Angeles, CA, November 20, 1997, paper 148f.

10.2 L.L. Tavlarides, "Acoustic Probe for Solid-Gas-Liquid Suspensions," Argonne National Laboratory, Argonne, IL, Ultrasonics/Acoustics Workshop, October 25, 1997.

10.3 M.A. Norato, A.S. Sangani, L.L. Tavlarides, M. Greenwood, "Acoustic Wave Propagation in Solid-Liquid Suspension," 16th Biennial North American Mixing Conference, MIXING XVI, Williamsburg, VA, June 16, 1997.

10.4 M.S. Greenwood, M.A. Norato, A.S. Sangani, P.D.M. Spelt, L.L. Tavlarides, "Ultrasound Attenuation Measurements in Solid-Gas-Liquid Slurries and the Solution of the Inverse Problem," Annual AIChE Meeting, Miami Beach, paper 187f, November 17, 1998.

10.5 M.S. Norato, A.S. Sangani, P.D.M. Spelt, L.L. Tavlarides, "Acoustics of Slurries Containing Small Amounts of Bubbles: Measurement and Theory for Forward and Inverse Problems," Annual AIChE Meeting, Miami Beach, paper 126b, November 18, 1998.

10.6 M. Norato, P. Spelt, M. Greenwood, A. Sangani, L.L. Tavlarides, "Acoustic Probe for Solid/Gas Liquid Suspension, 18th Biennial North American Mixing Conference, Banff, Canada. August 15-20, 1999.

10.7 M.S. Greenwood, M.A. Norato, A.S. Sangani, P.D.M. Spelt, L.L. Tavlarides, "Attenuation of Sound in Concentrated Suspension: Theory and Experiments," AIChE Meeting, Dallas, TX, Oct. 31-Nov. 5, 1999.

10.8 L.L. Tavlarides, "Acoustic Probe for Solid.Gas/Liquid Suspensions," DOE Characterization and Monitor Workshop, Atlanta, Georgia, Dec. 14-15, 1999.

10.9 L.L. Tavlarides, (with P. Spelt, M.A. Norato, M. Greenwood, A. Sangani), "Acoustic Probe for Characterization of Solid-Gas-Liquid Slurries," US DOE EMSP National Workshop, April 24-27, 2000, Atlanta, GA.

10.10 L.L. Tavlarides, A. Sangani, P. Spelt, M. Hedges, M.A. Norato and M. Greenwood, "Acoustic Probe for Characterization of Solid-Gas-Liquid Slurries," Tank Focus Area Midyear Review, Salt Lake City, UT, March 11-15, 2001.

11. Transitions

The work is being transitioned through the second funding period.

12. Patents

None

13. Future Work

Continuation of funding in progress.

14. Literature Cited

Atkinson, C.M. and Kytomaa, H.K., "Acoustic Properties of Solid-Liquid Mixtures and the Limits of Ultrasound Diagnostics-I. Experiments. J. Fluids Eng. **115**, 665 (1993).

Bonnet, J.C. and Tavlarides, L.L., "Ultasonic Technique for Dispersed Phase Hold-Up Measurements," I&EC. Res. **26**, 811 (1987).

Golcar, G.R., Colton, N.G., Durab, J.G., and Smith, H.D., "Hanford Tank Waste Simulants Specifications and Their Applicability for the Retrieval, Pretreatment, and Vitrification Processes," PNWD-2455/BNFL-RPT-012 Rev. 0, 2000.

Greenwood, M.S., Mai, J.L., and Good, M.S., "Attenuation Measurements of Ultrasound in a Kaolin-Water Slurry: A Linear Dependence Upon Frequency, J. Acoust. Soc. Am. **94**, 908 (1993).

Hylton, T.D. and Bayne, C.K., "Testing of In-Line Slurry Monitors and Pulsair Mixers with Radioactive Slurries," ORNL/TM-1999/111, July, 1999.

Martin, J., Rakotomalala, N., and Salin, D., Phys. Rev. Lett. **74**, 1457 (1995).

McLeod, F., "Directional Doppler Flowmeter," Intl. Conf. Med. Bio. Eng., Stockholm, 213 (1967).

Norato, M.A., "Acoustic Probe for the Characterization of Solid-Gas-Liquid Slurries," Ph.D. Thesis, Syracuse University, May 1999.

Spelt, P.D.M., Norato, M.A., Sangani, A.S., and Tavlarides, L.L., "Determination of Particle Size Distributions from Acoustic Wave Propagation," Physics of Fluids, Vol. 11 ns, 1065-1080 (1999).

Spelt, P.D.M., Norato, M.A., Sangani, A.S., Greenwood, M.S., and Tavlarides, L.L., "Attenuation of Sound in Concentrated Suspensions: Theory and Experiments," Jl. of Fluid Mechanics, **420**, 1-36 (2001).

Tavlarides, L.L. and Bonnet, J.C., "An Ultrasonic Technique for Dispersed Phase Holdup Measurements," US Patent No. 4,726,221 (1988).

Tsouris, C. and Tavlarides, L.L., "Volume Fraction Measurement of Water in Oil by an Ultrasonic Technique," I&EC Res. **32**, 998 (1993).

Tsouris, C., Norato, M.A., and Tavlarides, L.L., "A Pulse-Echo Ultrasonic Probe for Local Volume Fraction Measurements in Liquid-Liquid Dispersions," I&Res. **34**, 3154 (1995).

Yi, J.H. and Tavlarides, L.L., "Model for Hold-Up Measurements in Liquid-Liquid Dispersions Using an Ultrasonic Technique," I&EC Res. **29**, 475 (1990).

15. Feedback

None

16. Appendices

A1 – Publication 9.1
A2 – Publication 9.2
A3 – Publication 9.3
A4 – Publication 9.4