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Conference Report

INTERNATIONAL WORKSHOP ON ULTRASONIC AND DIELECTRIC CHARACTERIZATION TECHNIQUES FOR SUSPENDED PARTICULATES Gaithersburg, MD August 4-6, 1997

Report prepared by

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1. Introduction

Finely dispersed multiphase fluid systems, such as colloidal suspensions and microemulsions, may be found at some stage of nearly every industrial process; but the ability to characterize these complex materials in their natural, undiluted state is limited by concentration restrictions associated with conventional measurement techniques. Light scattering methods, for instance, require the test sample to be optically dilute (transparent); a condition rarely fulfilled in industrially relevant systems. There is also a growing need to develop on-line monitoring capabilities to support intelligent processing efforts in industry [1]. The development of new measurement technologies for concentrated dispersed systems requires cooperation and collaboration between industry, academia, and government laboratories. An International Workshop on Ultrasonic and Dielectric Characterization Techniques for Suspended Particulates was held at the National Institute of Standards and Technology, Gaithersburg, Maryland on August 4-6, 1997, to stimulate communication and encourage interaction among scientists and engineers working on emerging measurement technologies based upon the application of high-frequency acoustic or electric fields. This workshop was co-sponsored by the National Institute of Standards and Technology, the American Ceramic Society, and the American Chemical Society—Division of Colloid and Surface Chemistry.

The workshop was attended by 63 registered participants from 9 countries, including representatives from 18 industrial companies, 6 instrument manufacturers, 19 academic institutions, 2 national laboratories, and 1 foreign office of science and technology. The technical sessions consisted of 26 presentations emphasizing fundamental aspects, measurements in concentrated systems, instrument and sensor development, process control applications, and material applications. Measurement techniques included *electroacoustics, acoustic attenuation, acoustic velocity, and dielectric dispersion.* Examples were given from applications covering a broad spectrum of inorganic and organic systems, including advanced ceramics, clays, pigments, cement, phosphors, metal plating baths, food colloids, oil-water emulsions, coal-water slurries, biological cell suspensions, and many others. Recent technical advances in commercial instrumentation were also presented by the manufacturers. During an open forum held at the conclusion of the technical sessions, participants discussed issues related to the future development and application of ultrasonic and dielectric techniques. A consensus was reached on high-priority issues, which included the need for improved communication among researchers; it was generally agreed that this workshop has provided an important first step in that direction.

2. Conference Summary

The workshop consisted of 26 presentations, including 15 invited papers, organized into 5 technical sessions which spanned 2 1/2 days. An invited banquet-lecture on needs and opportunities for nondestructive evaluation in the ceramics industry was presented the first evening by Christopher Schilling of Ames Laboratory, Iowa State University. An open forum was held on the final day to discuss critical scientific and technological issues in the future development and application of ultrasonic and dielectric techniques. The following is a summary of the technical sessions.

2.1 Fundamental Aspects

This session consisted of three invited reviews focusing on each of the primary measurement fields relevant to this workshop: *acoustics*, *electroacoustics*, and *dielectric dispersion*.

Malcolm Povey, of the University of Leeds, England, opened the session with an overview of the application of acoustics in the characterization of particulate systems. Povey's presentation drew heavily from his 25 years of experience in working with food industry applications. He discussed the basic physics underlying ultrasound measurements, describing velocity and attenuation (loss) as related aspects of sound interaction with the dispersed phase. The primary loss mechanisms for colloidal systems were described as thermal, due to volumetric contraction and expansion, and visco-inertial, due to relative motion between the dispersed and continuous phases. Important theoretical contributions from Epstein and Carhart, Allegra and Hawley, and Alba, were duly noted. Povey covered three basic types of ultrasound measurement techniques. The simplest system, the *ultrasound profiler*, uses the pitch-and-catch technique in which sound velocity is measured at a fixed frequency (2.25 MHz in his example) across a vertically aligned cell using the time-of-flight method. The transducer is moved to produce a vertical profile of dispersed phase segregation processes, such as creaming and sedimentation. This technique is readily adapted for on-line applications. The second technique described was the *piston interferometer*, a wide-bandwidth continuous wave ultrasound attenuation method for determining particle size in suspensions. The interferometer uses a movable transducer with a variable gap width, and depends on a theoretical model to interpret attenuation spectra in terms of particle size. The most sophisticated acoustic measurement system described by Povey was the *frequency-scanning pulse echo reflectometer*, which uses Fourier transformation of pulsed acoustic signals to extract both velocity and attenuation data as a function of frequency. Again, particle size information is derived from the measured spectra using a theoretical scattering-loss model.

The second review was presented by Robert Hunter of the University of Sydney and Colloidal Dynamics Pty Ltd, Australia, on electroacoustic characterization of colloidal suspensions. The internationally distinguished colloid scientist began by discussing the critical role of colloidal suspensions in a variety of industrial applications. He followed with a brief overview of colloidal properties, including the basics of electrical double-layer theory with an emphasis on the importance of the zeta (shear-plane) potential in the stability of suspensions. The reciprocal nature of the two electroacoustic effects, the Colloid Vibration Potential (CVP) and the Electrokinetic Sonic Amplitude (ESA), was described; CVP and ESA are related through the complex conductivity, K^*. The ESA signal is proportional to the dynamic electrophoretic mobility of the colloids, which in turn is related to the zeta potential. The principle of operation of an *ESA spectrometer* was described in some detail. The Acoustosizer™ system[1] produced by Colloidal Dynamics measures the phase and amplitude of the dynamic mobility over a frequency range from 300 kHz to 12 MHz using a pulse wave method. Hunter described how the complex mobility is dependent upon the inertial response of the colloids in the applied field, and how this dependence is exploited, based on O'Brien's theory [2], to extract particle size data simultaneously along with zeta potential. It was also stressed that dynamic measurements yield a unique spectra for each zeta potential, making it possible to distinguish very high zeta potential values without the ambiguity associated with high mobilities determined in conventional d.c. electrophoresis. Some other key points touched upon during the presentation include the effects

[1] Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

of internal charge polarization on the ESA response of semiconductor colloids, the need to use empirical corrections at high solids concentrations (>10 % volume fraction), and the analysis of polydisperse suspensions. Hunter stressed that ESA is particularly well suited for high density contrast systems, such as ceramic slurries, but has been tested on a wide variety of industrially important materials including cement, coal-water slurries, and emulsions.

The final review was presented by Johan Sjöblom of the University of Bergen, Norway, on selected aspects of the dielectric properties of emulsions and solid particulate suspensions. He first reviewed basics associated with frequency dependent complex permittivity and the associated decomposition of this quantity into (real) permittivity and (imaginary) dielectric loss components, and how these components may be expressed in the case of having a single Debye-type relaxation. Sjöblom then reviewed time domain dielectric spectroscopy and experimental configurations that may be used when studying the effects of applied fields. The general modeling of dielectric relaxation in heterogeneous systems in the Maxwell-Wagner-Sillars approximation was reviewed with a view towards making applications to water-in-oil (w/o) emulsions and particulate suspensions. Several particular applications were then treated in greater depth. The first of these was an examination of the dielectric properties of w/o emulsions, an area in which Sjöblom has been a leading international contributor. He illustrated how dielectric spectroscopy is useful in monitoring creaming, flocculation, and sedimentation processes that lead to coalescence. The explicit shape effects attendant to the formation of linear dimers and trimers of droplets during flocculation were illustrated, and the frequency spectrum associated with charge polarization in droplets was qualitatively illustrated. The practical application of dielectric spectroscopy to analyzing chemical and physical components responsible for emulsion stability, in the case of crude oil emulsions, was illustrated. The onset of percolation induced by applied fields was illustrated, and this phenomenon was (1) shown to be analogous to percolation in microemulsions and (2) shown to obey a critical scaling law in static permittivity. Another major application area described was the analysis of sedimentation in solid particulate suspensions by dielectric spectroscopy, using time domain reflectometry. Kinetic and volume fraction effects were illustrated. The multivariate analysis of factors affecting suspension stability, as monitored by sedimentation, was illustrated for the case of disperse phase volume fraction, pH, salinity, surface hydroxylation, and temperature. A third application area comprising magnetic particle suspensions was illustrated for monodisperse polystyrene particles containing 25 % mass fraction of magnetic oxides. Gravity induced and magnetic field induced sedimentation were illustrated, and these effects were easily monitored using static permittivity measurements.

2.2 Measurements in Concentrated Systems (Part I)

The first of two sessions focusing on measurements in concentrated disperse systems consisted of five presentations by instrument manufacturers, who discussed the technology, underlying theory, and application of their commercial systems. Much of the discussion during this session centered on industrial applications, particularly on-line process monitoring.

Andrei Dukhin of Dispersion Technology, Inc. opened the session with a discourse on the benefits of combining acoustic and electroacoustic spectroscopy. Dukhin argued that this combination provides a more accurate description of dispersion properties than is possible by either technique alone. He presented a comprehensive review of the underlying measurement theories, pointing out various assumptions and limitations inherent in their application. Using a cell model approach, Dispersion Technology has been able to extend the quantitative application of viscous attenuation theory, in their DT Series instruments, up to 35 % volume fraction, whereas the basic dilute theory works only up to roughly 10 %. Examples were given of a wide variety of materials applications. In his discussion, Dukhin differentiated between dissipative (viscous, thermal, electroacoustic) and nondissipative (scattering) losses, setting off a running debate by theoreticians in the audience over semantic and fundamental differences of opinion concerning the description of attenuation mechanisms. This debate demonstrated the need for a standardized terminology in this sector of the ultrasonics field.

The second presentation was given by Steve Siano of Hewlett-Packard Company on radio-frequency dielectric spectroscopy. Siano presented a simple applications development approach based on a qualitative understanding of the relationships between the phase and measured parameters. He stated that dielectric spectroscopy is a quick, simple, nondestructive, and direct way to quantitatively and qualitatively analyze emulsions, suspensions, and biomass. He described the principle and application of the recently developed Colloid Dielectric Probe that uses electromagnetic induction to measure sample permittivity as a function of frequency, while avoiding the problem of electrode polarization. The speaker presented several examples from industrial applications, including quality control testing of polishing slurries in the semiconductor industry and determination of viable biomass concentration in fermentation baths.

The third talk was presented by Felix Alba of Felix ALBA Consultants, Inc. on sizing of concentrated particulates using ultrasound spectroscopy. The speaker discussed the technical and scientific basis of the Malvern Ultrasizer™ measurement system, which he helped develop. He described the basic steps involved in ultrasonic analysis (mathematical modeling, spectral measurement, and inversion mathematics), dealing with each aspect separately. Alba gave a very detailed review of the basic scattering theories, emphasizing the need to develop new theoretical approaches to the sizable problem of multiple scattering in concentrated systems.

The next presentation was given by Tonis Oja of Malvern Instruments, Inc., and focused on the measurement aspects of ultrasound spectroscopy. Oja gave a detailed description of the Ultrasizer™ instrument, which uses dual transmitter-receiver pairs to access a wider frequency range. He emphasized the key to obtaining the most complete information is to maximize the number of frequencies measured. Results obtained on test dusts and glazing materials suspended in water were favorably compared with low-angle light scattering measurements on diluted samples, while the resolving ability of attenuation measurements was evaluated on mixed particulate-phase calcium carbonate suspensions. Results of measurements on bitumen-water and cream-water/alcohol emulsions were also shown.

The final talk of this session was delivered by Peter Faraday of Sympatec, Inc. on particle size distribution analysis using the OPUS™ ultrasonic attenuation system in concentrated suspensions. Faraday focused on measurement related aspects, including accuracy, precision, and interferences. He discussed coupling of the measurement system with industrial processes in off-line and in-line configurations. He lent significant time to the problem of gas bubbles in ultrasonic measurements, and described a method for mathematically removing the effects of bubbles from the measured spectra. Faraday also presented a broad assortment of results from various industrial applications including crystallization, wet milling, food colloids, and petroleum-water emulsions.

2.3 Measurements in Concentrated Systems (Part II)

The second of two sessions focusing on measurements in concentrated disperse systems consisted of six presentations covering a broad spectrum of theoretical and measurement issues.

The session opened with an invited lecture by Ulrich Riebel of the Brandenburg Technical University, Cottbus, Germany, who spoke on the theory and applications of ultrasonic attenuation and velocity in dense suspensions. Riebel focused on the short-wavelength regime (i.e., particle size >> wavelength), giving a review on the physics of particle-wave interactions, which include entrainment, scattering, and resonances. Current theory for large particle extinction efficiency is based on the Mie scattering theory (1906) modified for ultrasonics; however, attenuation may be strongly influenced by resonances which are not sufficiently understood. Riebel devoted a significant portion of time to a discussion of particle-particle interactions in dense systems and their impact on ultrasonic measurements, listing three interactions which must be considered in the short-wavelength regime: multiple scattering, dependent scattering, and steric interactions. He concluded that multiple scattering is not, in most cases, the right explanation for high-concentration effects, and listed the proper order of importance for high concentration systems as (i) steric, (ii) dependent scattering, and (iii) multiple scattering. Riebel pointed out that, in general, ultrasonic detectors are not very sensitive to multiple scattered (incoherent) radiation.

The second presentation was an invited paper by Hemant Pendse of the Industrial Process Control Sensor Systems Program at the University of Maine, whose talk focused on particle shape effects in ultrasonic spectroscopy. He described a method he termed *active attenuation spectrometry* for measuring particle orientation evolution in suspensions subjected to squeezing flow in a continuously decreasing transducer gap width. Using oblate or prolate spheroid models and an assumed shape factor distribution based on electron microscopy and x-ray sedimentation results, the predicted attenuation spectra of clay suspensions were calculated and compared to the measured spectra obtained under specific flow conditions. Pendse concluded that the acoustic response is very sensitive to shape effects at high frequencies and high volume fractions, but relatively insensitive at low frequencies or low volume fractions. Potential commercial applications for this technology were also discussed.

The next presentation was given by Arvind Sharma of Los Alamos National Laboratory, on experimental aspects of particle systems characterization using ultrasonic attenuation spectroscopy. Sharma showed data which validates the performance of a commercial automated ultrasonic spectrometer system modified as an on-line sensor prototype. He indicated that new spectral features were observed when sound speed and attenuation spectra were presented simultaneously on a complex plane through the complex wave number. In particular, he found a complicated dependence of the attenuation coefficient on solids concentration at low and high frequencies; an effect which cannot be explained using simple quadratic relationships. Sharma proposed an equivalent acoustophoretic diameter to represent particle size distributions by means of a single empirical parameter.

The next paper was by Wei Han of Los Alamos National Laboratory, on a unified coupled-phase continuum model for acoustic attenuation in concentrated dispersions; the paper was presented by Hemant Pendse. There are essentially two ways of formulating the problem of ultrasonic attenuation in dispersed systems: scattered wave and coupled-phase. In the coupled-phase approach, developed by Temkin and Dobbins (1966) and subsequently improved by Harker and Temple (1988), the suspension is viewed as two phases (solid and liquid) that interact with each other through momentum and energy exchange. Han has modified this theory by coupling both thermal and viscous loss mechanisms, and has used an oscillating sphere-in-cell model to account for a range of particle concentrations and frequencies.

Tim Margulies of Johns Hopkins University gave the next presentation on the development of a continuum mixture theory for acoustic wave propagation in viscoelastic media with particulates or emulsions. Margulies outlined the derivation of balance and constitutive equations, and their application to coupled multi-phase systems. He also discussed potential applications for this type of mathematical analysis.

The final presentation of this session was given by David Scott of DuPont Central Research and Development, on industrial applications of ultrasonic attenuation spectroscopy. Scott's focus was in-line operation in high concentration systems where particle properties are impossible to determine with conventional techniques. He outlined many of the technical and scientific challenges to developing a robust measurement system, including air bubbles, transducer design, choice of particle size distribution function, and complications from particle morphology. He described a DuPont proprietary instrument which has been tested in various on-line and in-line operations. One example given was dispersion quality monitoring in a titania pigment system at 47 % volume fraction. The speaker stated that "further progress towards industrial application requires close collaboration" between those involved in the areas of "ultrasonic theory, particle science, sensor/instrument development, and process engineering."

2.4 Applications: Inorganic Materials

This session consisted of eight presentations covering a wide range of inorganic materials applications and involving commercial ultrasonic instruments. The first six presentations were invited papers.

Michael Stintz of the Technical University of Dresden, Germany, opened the session with a presentation on the characterization of inorganic colloids by ultrasonic attenuation spectroscopy. A variety of test materials and standard reference materials, were used to evaluate the precision and accuracy of ultrasonic measurements, including titania, alumina, and silica microspheres. Results were compared to more conventional methods, such as electron microscopy and laser diffraction.

The next speaker, Shin-ichi Takeda, of Okayama University, Japan, demonstrated the application of ultrasonic attenuation spectroscopy in the characterization of ceramic slurries. Well-characterized alumina and zirconia powders were used in these studies, which included the analysis of binary mixtures, the effect of suspension pH, and correlation with viscosity data.

Jorge Valdes of Lucent Technologies, Bell Labs, next described the application of electroacoustic measurements in dynamic colloidal systems used in the development of next-generation optical fibers. ESA measurements were used to determine the isoelectric point and dynamic mobility of complex colloidal silica dispersions undergoing dynamic chemical and physical changes.

Arunava Dutta of Osram Sylvania Products, Inc., showed how electroacoustic measurements are used in the development of photo-luminescent coatings which are prepared from complex dispersions of mixed phosphor powders. The presentation focused on the interaction of anionic polyelectrolyte dispersants with the dispersed phosphors.

Katy Barmak of Lehigh University described how ultrasonic attenuation spectroscopy is being used to characterize particulate size distributions in electrochemical deposition baths during electroplating and electrophoretic deposition of multilayered particulate-reinforced metal matrix composites and ceramic coatings. These materials are being developed for applications in jet turbine systems for power generation.

The next paper, by Lennart Bergström of the Swedish Institute for Surface Chemistry, was presented on his behalf by coauthor Eric Laarz. The speaker presented the results of two studies in which electroacoustic spectroscopy was used to characterize the surface properties of colloidal particles in concentrated ceramic slurries at 10 % volume fraction. Most of these studies focused on the effect of polymer dispersants on slurry properties. Electroacoustic measurements were also used to characterize changes in surface properties of silicon nitride powders following leaching and oxidation treatments. Comparisons were made with atomic force microscopy, rheology, and adsorption measurements.

Frank Hinze of the Technical University of Dresden, Germany, described the application of CVP measurements in the surface characterization of inorganic colloids, focusing on titania and silica systems. Electroacoustic results were compared favorably with dc electrophoresis measurements on diluted samples. A procedure for empirically correcting measurements at high concentration was also described.

The final paper of this session, by Ungyu Paik of Changwon National University, South Korea, was presented by the coauthor, Vincent Hackley, NIST Ceramics Division, on the application of electroacoustic analysis in advanced ceramic powder processing. The speaker highlighted key issues related to applications development, using several examples drawn from previous work on advanced ceramic systems to illustrate the advantages and limitations of this technique. In one example, the atypical electroacoustic response of a silicon semiconductor powder, used in the production of reaction-bonded silicon nitride, was compared to the "normal" response of a typical insulator powder such as silica.

2.5 Applications: Organics and Emulsions

The final technical session of this workshop consisted of four invited papers which focused on measurement applications in organic and emulsion systems.

D. Julian McClements of the University of Massachusetts opened the session by reviewing the application of ultrasonics in the food science field. The talk focused on velocity and attenuation measurements in emulsion systems, some examples of which included milk, cream, margarine, mayonnaise, and infant formulations. The bulk physical-chemical properties of these materials, such as shelf life, texture, stability, and taste, ultimately are determined by the colloidal properties, and therefore require measurement techniques that are sensitive to colloidal dimensions and can be applied in dense, optically opaque systems. Ultrasonics are used to obtain a variety of information in food emulsion systems, such as disperse phase volume fraction, droplet size distribution, and physical state. McClements presented several examples in which ultrasonic techniques have been employed with great success, such as monitoring of fat droplet crystallization, determination of solid fat content, and nondestructive monitoring of creaming profiles. He also described an ultrasonic imaging technique which was recently developed.

The second presentation was given by Yuri Feldman of the Hebrew University of Jerusalem, Israel, on time domain dielectric spectroscopy applications in organic particulate systems. A new experimental approach to time domain dielectric spectroscopy was described, wherein multiple time-window sampling was illustrated to yield spectra over the 100 kHz to 10 GHz frequency domain. He then reviewed some key aspects of his group's work on the application of dielectric spectroscopy to reverse microemulsions and then focused on new applications in aqueous suspensions of nanoparticulate organics. New results on correcting for fractal electrode polarization effects were illustrated for the case of conductive salt solutions. This scaling-based approach appears to provide correction for a diverse range of phenomena, including electrode porosity and specific electrode chemistries, such as surface group ionization and ion adsorption in the electrical double layer. The application of dielectric spectroscopy to aqueous dye suspensions was then illustrated and the scaling-law approach to correcting for electrode polarization effects was compared to the effects of time-window filtering. The relaxations observed for nanoparticulate dye suspensions were found to be in qualitative agreement with predictions of O'Brien [3] for the low and high frequency dispersion of aqueous suspensions.

Ralph Kornbrekke of The Lubrizol Corporation presented a paper on electroacoustic measurements of zeta potential for particulates suspended in organic media. Industrial applications include the dispersion of soot particles produced in engine oil. Kornbrekke gave a comparison of the properties of organic liquids, relative to aqueous media, in relation to their effects on particle dispersion, electrostatics, and interpretation of zeta potential measurements. He showed results of experimental studies on carbon black (a model for soot particles) dispersed in various aromatic and cycloparaffinic oils and solvents. ESA measurements at high applied field strengths (1000 V/cm) were used to characterize particle charge behavior in the low dielectric constant media.

The final paper of this session, and of the workshop, was presented by Koji Asami of Kyoto University, Japan, on dielectric relaxation spectroscopy in biological cell suspensions. Asami is perhaps the leading authority on the application of dielectric spectroscopy to the analysis of cell suspensions. He reviewed the application of shell models, in the Maxwell-Wagner-Sillars (MWS) polarization sense, of cells and reviewed the most prevalent relaxation processes identified in various frequency ranges. The low-frequency spersion, occurring below a few kHz, is assigned to counter-ion displacement about cell membranes. This relaxation is often obscured by electrode polarization effects. The β-dispersion found in cell suspensions occurs over the 1 kHz to 1 GHz range and arises from MWS polarization about the relatively insulating cellular membrane. The γ-dispersion occurs at frequencies above 1 GHz and results from dipolar reorientation of water molecules retarded by close association with cellular chemical components, principally proteins and phospholipids Asami illustrated these phenomena with data obtained for erythrocytes, lymphocytes, and plant protoplasts. The lecture was concluded with two experimental innovations. The first was an in-depth description of a toroidal probe, also illustrated in the earlier presentation by Siano. This probe completely obviates issues surrounding electrode polarization since only inductive coupling is involved (no electrodes). The second was a brief review of an exciting and new type of microscopy based upon a micro-scanning dielectric probe. This scanning dielectric microscope was illustrated to generate raster-scanned images of capacitance and conductance associated with cells grown on steel foil. This new microscopy offers the possibility of gaining new insights into cell structure.

3. Future Directions and Key Issues

The need for establishing clear terminology was underscored in the discussions. This need was expressed particularly with respect to describing energy loss mechanisms in acoustic measurements.

It was generally agreed that much more work needs to be done in articulating theoretical and practical approaches to handling multiple scattering phenomena in acoustics. In this vein, particular treatments aimed at resolving particle-particle interactions, interference phenomena, and incoherent ultrasound are needed. It was suggested that ultrasonic theory be compartmentalized according to different wavelength ranges.

It was suggested that acoustic and dielectric spectroscopy by usefully applied to networks and gels. Such applications appear feasible, but are as yet untested. Another suggestion was to apply acoustic spectroscopy to the analysis of rheology. At present it seems such applications would be too dangerous from an interpretive point of view, and much more work is needed to connect micrometer-scale and macroscale phenomena. Since acoustics are highly suitable for noninvasive and in-line monitoring, such developments would be highly welcomed.

It was suggested that the time might be right to combine dielectric spectroscopy and electroacoustic technologies. It was also suggested that ultrasonics and electroacoustics might beneficially be combined. Much more work needs to be done to obviate problems associated with electrode polarization in conducting fluids. This has been a traditional problem in the application of dielectric spectroscopy to aqueous systems and suspensions.

The further development of standards for testing instruments at high concentrations and in suspensions of particles of different sizes was stressed as an outstanding need for the academic and industrial practitioners. The need for improved communication among researchers and input from process engineers for developing on-line measurement systems was also articulated.

4. More Information

The workshop proceedings [4] will be published by the American Ceramic Society, P.O. Box 6136, Westerville, Ohio 43086-6136 (ISBN: 1-57498-034-3).

To obtain further information, or to be placed on the mailing list for future workshops, write to Vincent Hackley, National Institute of Standards and Technology, MATLS A256, Gaithersburg, MD 20899-0001, or send email to ultrasonics@nist.gov.

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6. References

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