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Using a multi-frequency acoustic backscatter system as an *in situ* high concentration dispersion monitor

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HIGHLIGHTS

- Use of an ABS is demonstrated as an *in situ* concentration monitor.
- Experimental echo responses are compared to theoretical fits.
- Theory found to overpredict concs. >2.5 g/L, due to interparticle scattering.
- A novel interpolated differential approach is then used to correlate concentration.
- Attenuation increase with respects to conc. found to be independent of system depth.

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ABSTRACT

This paper demonstrates the potential of an *in situ* acoustic backscatter system (ABS) to measure particle dispersion concentrations in small and large scale mixing vessels. The ABS unit employs 1, 2, 4 and 5 MHz transducers that emit ultrasonic pulses and receive the resultant echo backscatter signals, with the strength of the return being related to particle concentration. In small scale studies (where the effect of depth-wise attenuation is effectively ignored), a peak is measured in the strength of the echo responses at intermediate concentrations, due to a balance of the backscatter and attenuation components on the overall signal. The average measured responses were then compared to backscatter theory, which suggested that such analysis is invalid for systems with particle levels greater than $\sim$2.5 g/L and qualitative approaches may be necessary to correlate concentration.

More detailed analysis is undertaken in a larger-scale system, where the deviation between expected depth-wise theoretical response and real experimental echo decays are quantified for individual frequencies. It is shown that theoretical estimations heavily over-predict the strength of backscatter echoes at higher particle concentrations, likely due to increasing inter-particle scattering, and such effects are most evident for the highest frequency tested. Because of these limitations, dispersion concentration is correlated using qualitative approaches. For the 4 and 5 MHz responses, which had approximated linear depth-wise decays (on a dB scale), it is found that the gradient of the attenuation decay slope (in dB/m) increases linearly with respect to particle concentration, which allowed the formation of a direct correlation relationship. For the 1 and 2 MHz responses, the interpolated differential is calculated for specific depth points. Again, a linear correlation is established between the gradient of attenuation and particle concentration, where importantly, it was found that this gradient is independent of dispersion depth. This result highlights the possibility of measuring concentration variation in larger scale systems, simply from the associated differential attenuation changes, and indicates the potential of acoustic techniques for the monitoring and characterisation of industrial multiphase systems.

1. Introduction

In many solid–liquid treatment processes, for example in minerals processing or wastewater treatment systems, it is advantageous to be able to monitor particle concentrations through the various unit operations. An ability to efficiently and cheaply monitor changes during transport, segregation in storage or enhance understanding of separation in thickeners and clarifiers is a challenge encountered

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throughout multiphase industries. Indeed, operators increasingly require *in situ* or on-line monitoring technologies to better control particle processing and increase operational efficiency, without the time and intrusion problems associated with physical sampling.

For many pipe transport operations, particle concentrations can be gauged remotely with on-line densitometers (AWWA, 2001; Baker, 2000; Yoder, 2001) using techniques such as gamma radiation, electrical tomography or acoustics; where the differing absorbance or conductive/impedance properties of particles in relation to the bulk liquid medium, are utilised to measure changes in the overall fluid density (Bamberger and Greenwood, 2004; Cattle and West, 2006; Kaushal and Tomita, 2007; Stanley and Bolton, 2008). For use in tanks or thickener type processes, however, remote *in situ* instrumentation capable of profiling concentration changes is not as developed. Gamma ray and electrical depth probes do exist (Bolton et al., 2007; Farrow et al., 2000; Johnston and Simic, 1991; Nasr-El-Din et al., 1996; Richardson and Holdich, 2001; Stanley and Bolton, 2008; Thermo, 2006; Thien et al., 2011); although, the technologies are costly, and full length devices capable of multipoint profiling may require significant intrusion.

Ultrasonic pulse analyses however do offer the possibility to study particle segregation for a great range of processes with minimal intrusion and at low cost. Here, the scattering or absorption–attenuation of sound penetrated through dispersions can be correlated to a number of particle parameters. Separated transmitter–receiver systems can be used as on-line monitors in pipes and small scale mixing systems to directly study particle concentration as well as size, aggregation and crystal growth (Hauptmann et al., 2002; Jin Choi et al., 2006; Mougin et al., 2003; Shukla et al., 2010; Sung et al., 2008; Tourbin and Frances, 2009). Such devices have also been used in larger depth scales to measure segregation and settling in columns (Shukla and Prakash, 2006; Shukla et al., 2007; Soong et al., 1997; Tallon et al., 2003; Tsouris et al., 1990). The downside to separated transmitter–receivers is that scattering–absorption information is averaged over the entire distance between the transducers, and hence multipoint depth profiling is not available from a single probe instrument.

Single transducer systems offer a more flexible approach, where the piezoelectric crystal probes both generate an acoustic pulse and receive the return echo signals. These types of monitors are encountered extensively in environmental sedimentology applications, where they are used to measure particle velocities and transport in natural flows such as rivers and estuaries (Thorne and Hanes, 2002). Acoustic Doppler profilers (which quantify the Doppler shift of the baseline frequency) are a standard technique to track particle velocities in both environmental and engineering applications (Harbottle et al., 2011; Hosseini et al., 2006; Kostaschuk et al., 2005; Kotze et al., 2011), while acoustic backscatter systems (ABS) which more simply measure the returned echo voltage (*i.e.*, the amplitude shift) of an ultrasonic pulse, can be used in dilute conditions as a direct correlation of concentration (McLelland, 2010; Shi et al., 1999). In addition, theoretical analysis has been used to fully resolve backscatter profiles from ABS measurements, for well defined spherical glass dispersions (Betteridge et al., 2008; Thorne and Hanes, 2002), allowing quantification of concentration values from measured echo responses. Despite the use of acoustic backscatter systems in natural sedimentary environments, their utilization in engineering or processing applications is not yet established, due primarily to the higher particle concentrations which can significantly reduce the quality of backscatter signals.

In an earlier publications, we looked into both the use of an ultrasonic velocity profiler (Hunter et al., 2011) and an acoustic backscatter system (Hunter et al., 2012) to investigate particle concentration changes in small scale batch settling systems. Significantly for the current study, the ABS proved capable on this smaller scale to measure particle changes over time in a settling flocculated system, using appropriate well-mixed responses for correlation (Hunter et al., 2012). However, a number of important questions remain into the potential of these devices for profiling in larger scale systems. First, information is required on the concentration limit to which theoretical quantitative approaches (used in dilute environmental systems) can be applied, due to the greater particle ranges encountered in engineering processes. Second, the depth-wise acoustic backscatter–attenuation relationships at large metre length scales need to be investigated, to understand whether qualitative correlation approaches (such as undertaken previously on the batch scale by the current authors (Hunter et al., 2012)) could also be used to measure concentration at greater depths.

In this study, a series of investigations were performed on homogeneous glass powder dispersions in both large and small scale systems. First, the acoustic response at small scales over a high particle range was established to highlight the general backscatter–attenuation behaviour. Second, acoustic responses were profiled for a larger metre length system and compared to those expected from theoretical analysis. Lastly, echo responses for the larger scale system were qualitatively analysed to produce concentration correlations, based on the linear change in attenuation.

2. Theory

The theoretical approach to understanding single transducer backscatter response has been developed in a number of papers for well defined and dispersed, spherical glass and sand particle systems (*e.g.*, (Betteridge et al., 2008; Crawford and Hay, 1993; Meral, 2008; Thorne and Hanes, 2002; Thorne et al., 1993)). Definitions as used for the current study are summarised here. Eq. (1) displays the standard definition for the backscattered voltage signal V_{rms}, from a homogenous suspension; where K_s is the scattering constant, K_t the transducer constant, C the particle concentration, L is the distance of length from transducer, ψ is the spreading constant and α the signal attenuation.

$$V_{rms} = \frac{K_s K_t C^{1/2}}{L\psi} e^{-2L\alpha} \tag{1}$$

The spreading constant ψ accounts for the departure from spherical spreading within the transducer 'near-field' region (Downing et al., 1995), and for measurements in the 'far-field' is equal to 1 (only a far-field analysis was conducted for the present study). The transducer constant K_t should be independent of system variables, and relates to particular material differences of each transducer's signal response. It is generally defined by rearranging Eq. (1) and solving for K_t in a well defined calibration system (Betteridge et al., 2008). Such a procedure was taken by the manufacturer (Smerdon and Thorne, 2008) to produce values of K_t for each transducer used in this study, with resulting constants shown in Table 1.

K_s equates to the scattering properties of the dispersion material, and is a combination of the complex scattering form function (f), the particle density (ρ_p) and particle radius (r). The overall attenuation is an additive of the water attenuation (α_w, which can be defined for a particular temperature and frequency (Meral, 2008)) and the attenuation due to the particles α_p. Both K_s and α were calculated, as defined in Eq. (2), where additionally, χ is a complex function describing the scattering attenuation from the particles.

$$K_s = \frac{f}{\sqrt{\rho_p r}}, \quad \alpha = \alpha_w + \frac{3\chi C}{4r\rho_p}, \tag{2}$$