Acoustic Measurement and Monitoring in Dry Particulate Systems: Inspiration, Education, Application, Appreciation

Clive E. Davies[1], Stephen J. Tallon[2] and Emile Webster[1]

[1] School of Engineering and Advanced Technology, Massey University,
Private Bag 11 222, Palmerston North, New Zealand
C.Davies@massey.ac.nz

[2] Industrial Research Limited, Private Bag 31-310
Lower Hutt 5040, New Zealand

ABSTRACT

Techniques for the use of audio-frequency sound waves in the measurement of flow rate and particle size and the estimation of the volume of material contained in partially closed vessels are described and discussed.

INTRODUCTION

Non-invasive interrogation of systems and processes involving dry particulate materials is particularly challenging. X-rays and γ-rays, for example, offer the prospect of truly non-invasive monitoring of material inside metal pipe work or metal containment as typically found in industrial practice, but require extensive calibration and are usually subject to licensing regulations. Exploitation of inductance and capacitance is limited by constraints on the properties of the pipe work or process vessel holding the material which must be modified to be partly, and usually significantly, non-metallic.

Interrogation by acoustic waves is not a universal panacea to these difficulties, but while especially attractive and effective in dilute flow systems, can also be used in some situations with bulk solids.

In this paper we revisit earlier work on measurement and monitoring of flow rate in both dilute and dense flow systems, particle size measurement, the effect of frequency on acoustic propagation velocity in dense systems, and also report on work in progress on the use of Helmholtz resonance to determine the volume fraction of bulk solids in a partially closed vessel.

DILUTE PNEUMATIC CONVEYING

Natural pressure waves are generated in pneumatic conveying systems, particularly by reciprocating air movers. These waves propagate as sound waves along the pipe and in a dilute system such as pneumatic conveying lines can travel for some distance. Changes in the velocity and magnitude of these waves along the pipe contain information of the flow velocity and concentration of the gas and solids phases and can be used for flow measurement[1-3]. Approximately logarithmic decay in pressure wave intensity was observed with increasing particle concentration, and the conveying gas velocity correlated well with changes in the propagation velocity of the waves, as in figures 1,2. Measurements can be made using a single pressure sensor located downstream of the solids feed point, although it is necessary to minimise the dead volume between the pipeline and the sensing surface of the pressure transducer, and depends on the existence of a constant and reliable source of sound.

To remove this latter limitation it was demonstrated[4] that an introduced wave of a constant frequency could also be used. The use of an introduced sound wave also allows a frequency to be picked that minimises interference effects from other sources of sound waves and from sound wave reflections related to the pipeline geometry. The preferred sound frequency is one which is low enough for the waves to propagate as a one dimensional wave. The frequency limit for this to occur decreases with increasing pipe diameter[4], and is in the mid to low audible frequency range for typical pneumatic conveying pipe sizes. Tallon and Davies[4] report that the measurement method can be applied to either vertical or horizontal conveying. Measurement of the pressure waves at two consecutive points along the pipeline is also reported, so that a relative attenuation between the two points can be measured. This allows a localised measurement to be made, preferably in a region of fully developed flow.

To further improve the measurement reliability it is possible to measure sound waves propagating in both an upstream and downstream direction from a centrally located sound source (figure 3), or between two axially spaced sound sources (figure 4)[5]. The velocity of the sound waves in the downstream direction is faster than the upstream velocity because of the effect of the convective motion of the gas phase that the waves are passing through. The convective velocity is calculated simply from the difference between the upstream and downstream velocities, i.e. the sum of the measured upstream velocity and downstream velocities divided by two. For turbulent and largely plug flow conveying conditions with small particles, the convective velocity is essentially equal to the mean gas velocity.

To calculate a solids mass flow rate from the solids concentration, it is assumed that the solids velocity is related to the gas velocity by a small but constant difference, or slip velocity. The estimated solids velocity is then multiplied by the measured solids concentration to give a mass flow rate. The slip velocity varies under different flow conditions, and at different points in the pipeline where fully developed flow may not have developed[6], but it has been shown that the assumption of a constant slip velocity has little effect on the accuracy of solids flow measurement if the system is calibrated against known solids flow rates[4]; see figure 5. This calibration can be achieved, for

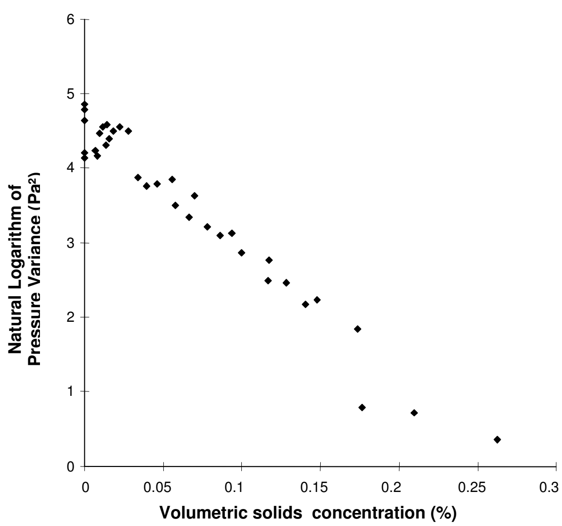

Figure 1. Change in intensity of natural sound waves in a pneumatic conveying line with changing solids concentration. Measured at a single point downstream of the solids feeder.

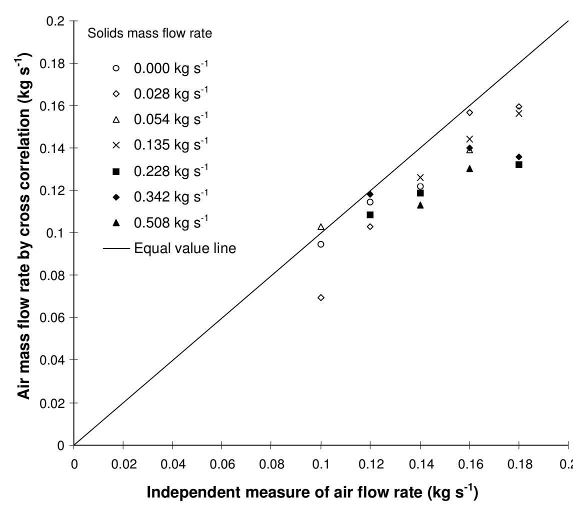

Figure 2. Air mass flow rate calculated from the increase in the sound wave propagation speed due to the convective flow of the gas phase. Sound velocity measured between two points 3m apart. The measurement is influenced by the solids flow rate.

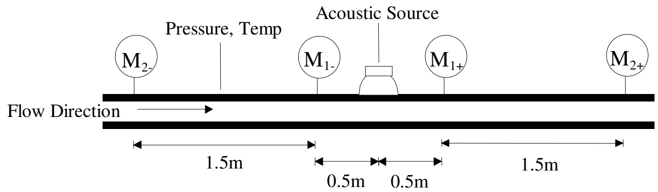

Figure 3. Flow measurement layout using a single acoustic source. Dimensions are indicative for use in a 3" diameter conveying line.

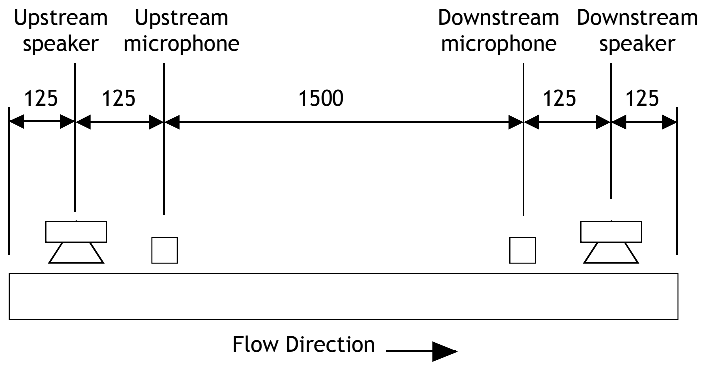

Figure 4. Flow measurement layout using two acoustic sources. Dimensions in mm are indicative for use in a 3" diameter conveying line.

example, by injecting a known mass of solids into the system and integrating the response over time[5].

Solids flow rate measurement has been demonstrated in dilute conveying systems up to 8" in diameter[7] (see figure 6), for conveying velocities up to 35m s^{-1}, and solids concentration up to 0.2% by volume. Better results are achieved if the measurement is made a sufficient distance downstream from the solids feed point or from pipe bends so that the flow is more fully developed.

Theory for the propagation of sound waves through a dilute suspension is described by Tallon,[8] based on theory by Gregor and Rumpf.[9] Accurate calibration of the relationship between attenuation and solids concentration is difficult to achieve theoretically, but good correlation between measured and calculated acoustic velocities was observed. Changes in the propagation velocity due to changes in the particle size could also be predicted and it is possible to use this to give an in-line measurement of particle size, and to compensate for particle size effects on the mass flow rate measurement[10].

DENSE PHASE FLOW SYSTEMS

Sound waves will also propagate through dense particle beds and can be used for measurement of a number of flow and state properties in dense flow systems such as downcomers, fluidised beds, dense phase pneumatic conveying and granulation systems.

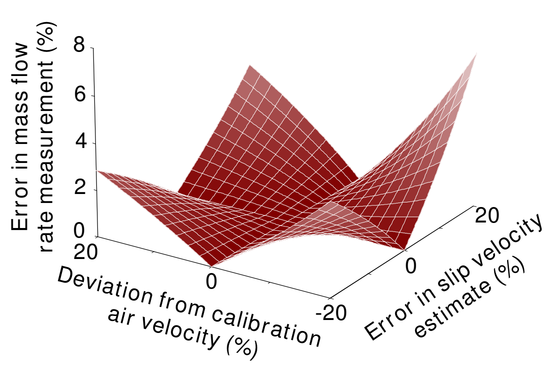

Figure 5. Error in solids mass flow rate measurement when the system is calibrated against a known mass of material. Errors in the slip velocity estimate do not have a large effect on measurement accuracy.

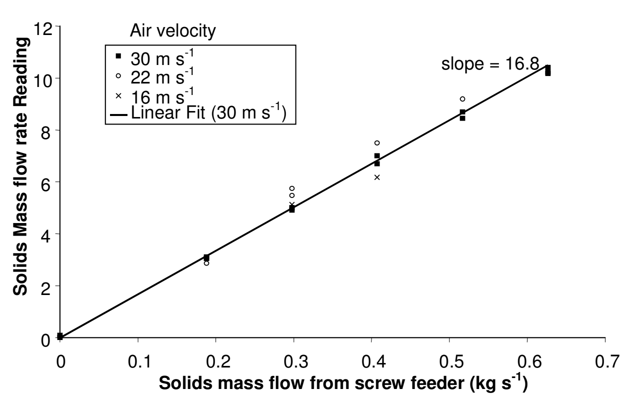

Figure 6. Mass flow rate of coal measured in an 8" diameter conveying line.

Sound waves will propagate through the interstitial gas phase, and also through the solid matrix if sufficient particle to particle contact exists. Interstitial sound waves are rapidly attenuated in a dense system but can still be used for measurement over small distances. Natural pressure waves generated by a gas pulse in an L-valve feeder, for example, have been used to give an indication of linear flow velocity in the conduit above the feeder[11] by measuring changes in the wave propagation velocity.

A more accurate method for flow measurement in a vertical conduit was achieved[12] by propagating introduced sound waves across the diameter of the conduit. The presence of natural variations in the packing voidage created measurable variations in the signal strength which could be tracked between two axial positions to give a flow velocity, as in figures 7,8. This measurement approach was demonstrated[12] in column diameters up to 200mm, and for mass flow rates up to 20 tonnes per hour. Best results were achieved for systems with a particle size greater than 1 mm and materials with plug flow characteristics.

Acoustic propagation velocity through the interstitial gas phase in dense particulate systems has been modelled by Tallon[8] by assuming that the solids particles oscillate in response to the motion of the gas phase. At low frequencies the particles follow the motion of the gas phase well and the propagation velocity is reduced by the greater inertia of the solids phase. At higher frequencies the particles become more stationary and the gas phase propagation velocity is only reduced by the tortuous path length through the particle bed. A comparison with experimental measurement is given in Figure 9.

The sound wave velocity through a packed or fluidised bed is a strong function of voidage and particle size. Velocity measurements in packed beds of a range of different materials are shown in figure 10 plotted against the Carman-Kozeny[13] flow factor. It is also possible to monitor changes in

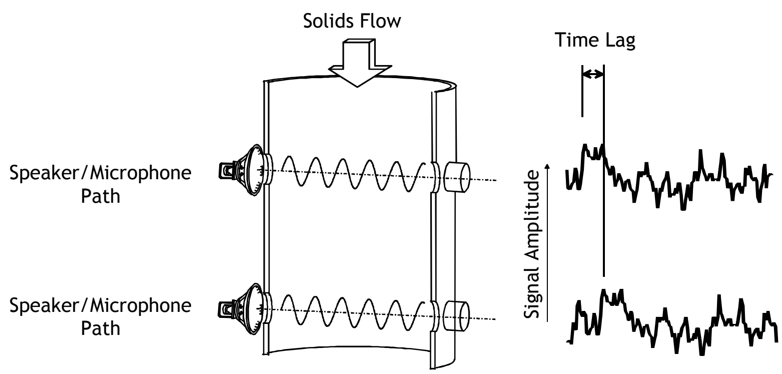

Figure 7. Principle for solids velocity measurement in bulk gravity flow in a conduit.

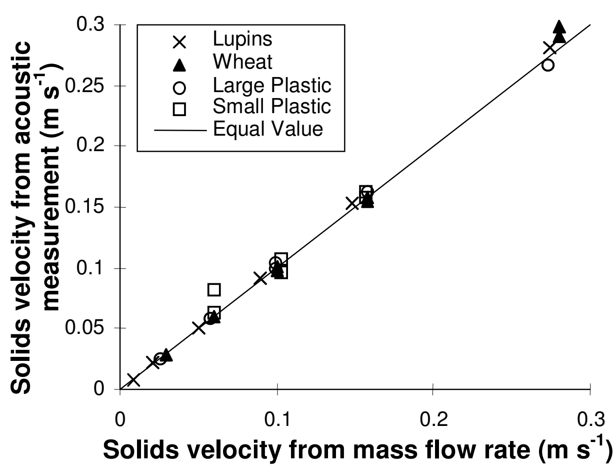

Figure 8. Velocity measurements in a 190 mm diameter conduit for a range of materials.

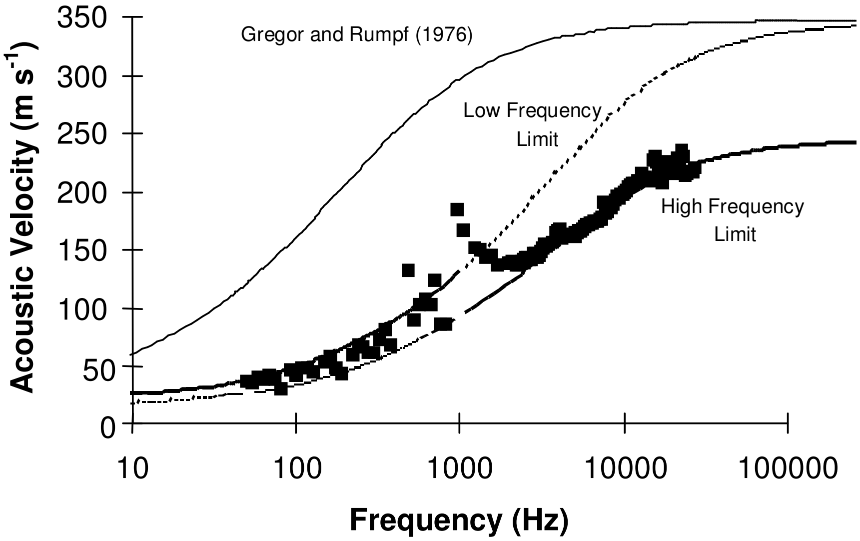

Figure 9. Acoustic velocity measurements through a packed bed of casein. Predicted acoustic velocity described by Tallon,[8] modified from theory by Gregor and Rumpf.[9]

particle size using acoustic velocity measurements.[14]

Acoustic measurements in a dense phase pneumatic conveying system have been used to measure conveying regimes, slug velocity and length, and an approximate solids mass flow[15].

MATERIAL VOLUME AND FILL FACTOR

When a chamber which is connected to the surrounding atmosphere by an open port or ports is excited by an acoustic stimulus, it resonates at a frequency that is determined mainly by the volume of the chamber and the length and diameter of the ports; this is known as Helmholtz resonance. If an object – which may be a massive solid, a powdered or granular material, or a liquid - is placed in the chamber, the volume of the chamber is reduced and the resonant frequency changes, permitting the

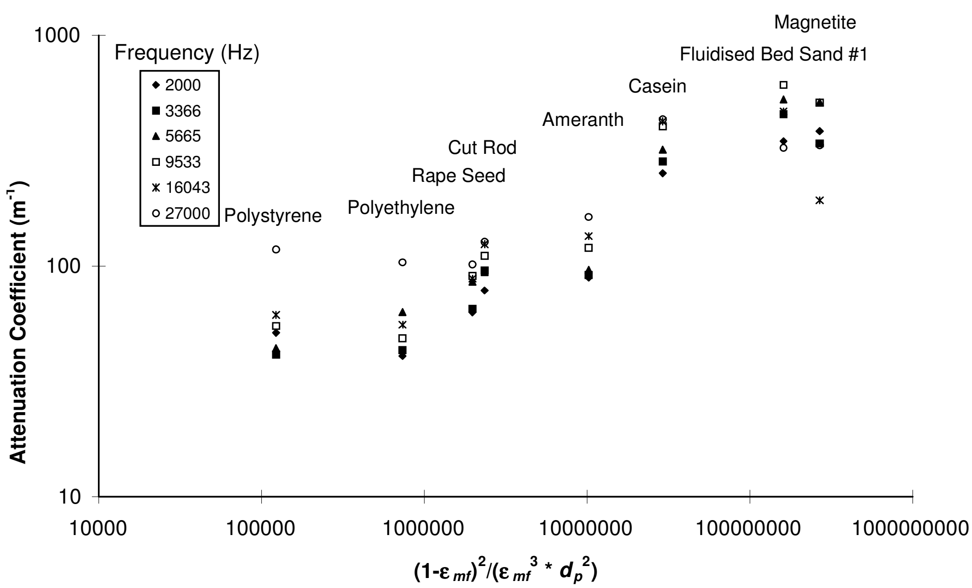

Figure10. Acoustic attenuation in a static bed of particles, plotted against the Carman-Kozeny flow resistance factor.

volume of the introduced object or material to be estimated.

The resonators used in this work were made from Perspex tube with a nominal inside diameter of 140 mm. Figure 11 is a photograph of a 3L resonator with a port 170 mm long and an inside diameter of 22 mm. Excitation was provided by an 8 inch infinite baffle loudspeaker which gave a linear response over the frequency range of 80 Hz to 500 Hz expected in the experimental programme; the loudspeaker was driven by a 100 W stereo audio amplifier. Two PCB103A sound pressure microphones were used to sense the sound signals; one was located centrally in the base of the chamber and the other at the top of the 170 mm port.

The materials used were water; marbles with a mean diameter of 24 mm, termed large marbles; marbles with a diameter of 15 mm termed small marbles; glass ballotinti with a Sauter mean diameter of 261 µm; glass ballotini with a Sauter mean diameter of 713 µm; and silica sand with a Sauter mean diameter of 166 µm. In all experiments the mass of the test material in the chamber was recorded, and its volume calculated using its actual density, *i.e.* the density of water, and the particle density in the case of the ballotini and sand. Full experimental details are given by Webster and Davies.[16]

Figure 12 is a comparison of measured and predicted resonant frequencies for a calibration run using water, and figure 13 is a plot of actual volume of the material in the chamber, *viz* the mass multiplied by the particle density, and predicted volume.

It is apparent that for the water calibration the resonant frequencies measured experimentally and the values predicted by theory are in excellent accord. The results for materials placed in the chamber fall into two broad groups. For large marbles, small marbles, and water, the agreement between theory and experiment is very good. For the sand and ballotini, the relationship between measured and predicted volume is non-linear over virtually the whole of the range investigated. The relationship between bulk volume of the sand and ballotini, as opposed to the actual volume as used here, and predicted volume, will be discussed elsewhere.

CONCLUSIONS

Audio-frequency sound waves are a versatile tool which can be used to interrogate particulate systems for information on flow rate, particle size, and the extent to which a partly closed chamber is occupied by a granular solid. Work to date has demonstrated the potential of acoustic diagnostic techniques for extracting useful and meaningful information from particulate flows in dilute phase pneumatic conveying pipelines, from flows in dense phase pneumatic conveying, from dense gravity flows of bulk solids and from static systems where bulk solids are contained in partially closed chambers.

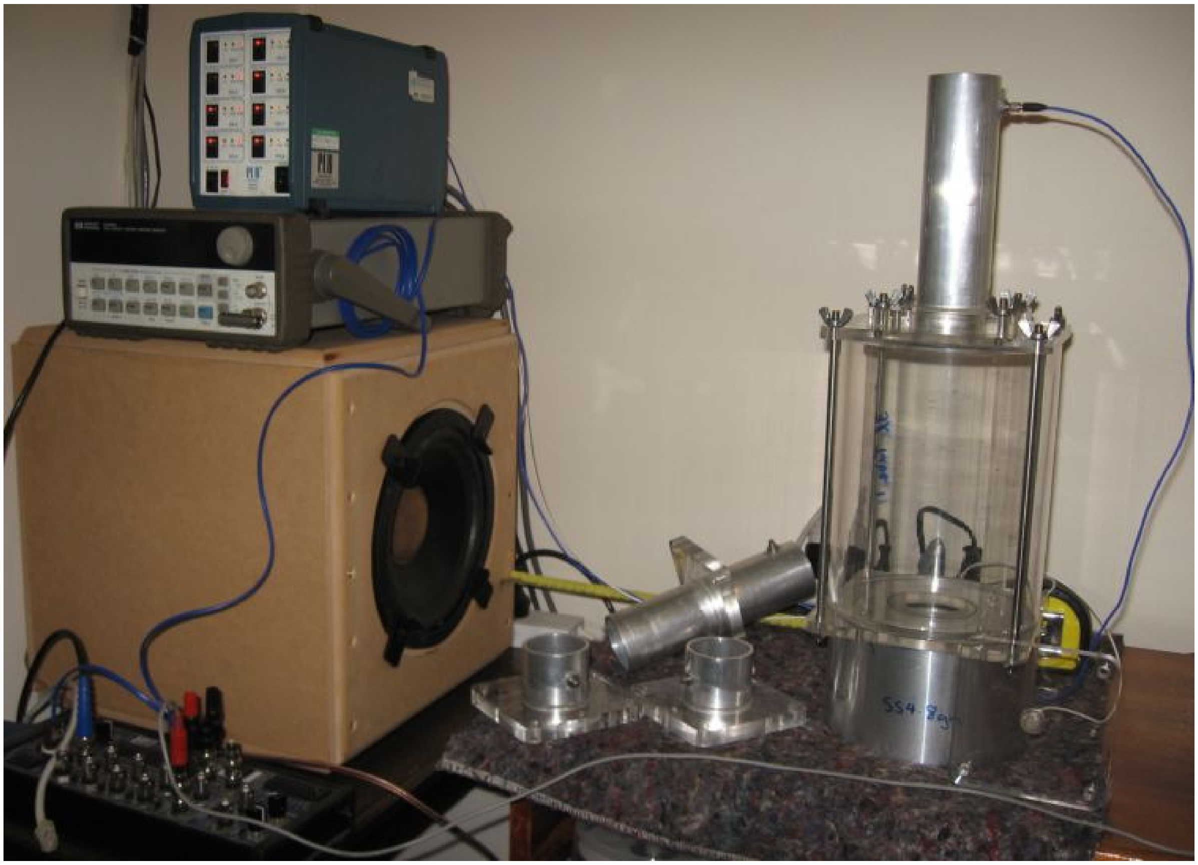

Figure 11. Photograph showing experimental equipment: loudspeaker, left; resonator, right; signal generator on top of loud speaker.

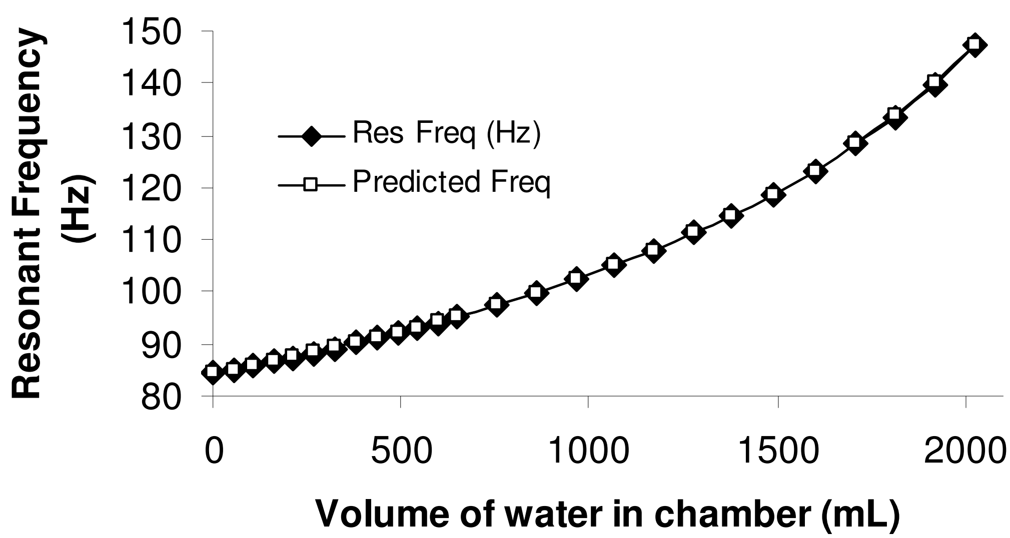

Figure 12 Comparison of resonant and predicted frequency in calibration test with water.

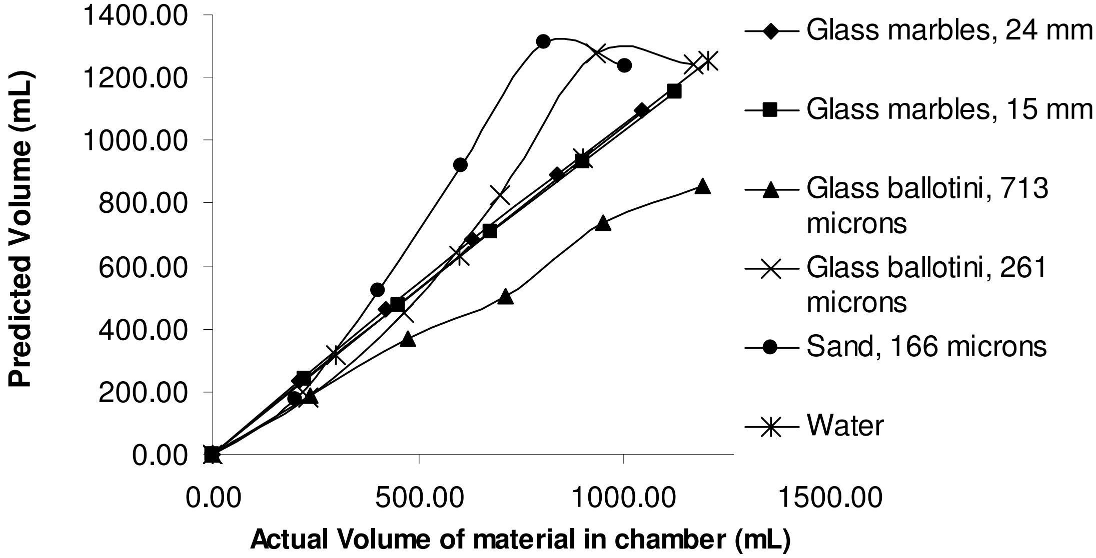

Figure 13. Comparison of actual and predicted volumes of material in 3 L resonator.

ACKNOWLEDGEMENT

In the late 1980s, CED visited Dr George Klinzing at the University of Pittsburg in connection with his interests in bulk solids handling. During the visit, he became aware of the relevance of sound to some diagnostic techniques in dilute pneumatic conveying. That was the beginning of a long and enduring interest in the use of sound as a diagnostic tool in a number of different physical systems. All the work discussed here was spawned by that first visit to Dr Klinzing's laboratories. Over the intervening years, CED and SJT have had many discussions with Dr Klinzing and we gratefully acknowledge the inspiration he has provided to us both.

REFERENCES

1. Tallon, Steve, and Davies, Clive E, 1994; The Use of Pressure Fluctuations to Characterize Gas and Solids Flow Rates in Dilute Phase Pneumatic Conveying, Proceedings of Chemeca 94, Chemical Engineering Conference, Perth, Australia, 25 to 28 September.

2. Tallon, S., 1995, On the characterisation and flow measurement of pneumatic conveying systems using static wall pressure measurements, Masters Thesis, Chemical and Process Engineering, University of Canterbury, Christchurch, New Zealand.

3. Tallon, Steve, and Davies, Clive E; 1995. Flow rate monitoring and measurement in dilute phase pneumatic conveying using pressure fluctuations, *Developments in Fluidization and Fluid Particle Systems*, AIChE Symposium Series, 91, (308), pp137-146.

4. Tallon, Stephen and Clive E Davies, 1996. Velocity and attenuation of sound: Application to flow rate estimation in pneumatic conveying, Powder Handling and Processing, *The International Journal of Storing, Handling and Processing Powder*, 8, (4), pp329-336.

5. Tallon, Stephen and Clive E Davies, 1997, Use of the attenuation of acoustic pulsed pressure waves for concentration measurement of gas-solid pipe flow, *Advances in Fluidization and Fluid-Particle Systems*, AIChE Symposium Series 317, 93, 1997, pp136-140.

6. Tallon, S.J., Davies, C.E., (2000), "The effect of pipeline location on acoustic measurement of gas-solid pipeline flow", Flow Measurement and Instrumentation, Volume 11, Number 3, pp 165-169.

7. Tallon, S., Davies, C.E., Levy, E.K., Yilmaz, A., (2001), "Measurement of solids flow rate in pneumatic conveying pipelines", Proceedings of the 2001 joint conference of SCENZ/FEANZ/EMG, Auckland, New Zealand, April 9th to 10th, pp 49-51.

8. Tallon, S.J., The application of acoustics to the monitoring of gas-solid processing systems, PhD thesis, Chemical and Process Engineering, University of Auckland, Auckland, New Zealand, 2001.

9. Gregor, W., Rumpf, H., (1976), "The attenuation of sound in gas-solid suspensions", Powder Technology, Volume 15, pp 43-51.

10. Stephen Tallon and Clive E Davies, 1997. In-line Monitoring of Particle Size Changes in a Pneumatic Conveying Pipeline using Pulsed Sound Waves, Chemeca 97, Rotorua, New Zealand, 29 September to 1 October.

11. Clive E Davies and Stephen J Tallon , (2004) "A pressure pulse method for monitoring flow rate in dense down flows of Geldart Group B particles", Powder Technology, Volume 148, 2004, pp 102-105

12. Tallon, Stephen, Davies, Clive E and Bernard Barry,1998. Non-intrusive velocity measurement in a downcomer, Fluidization and Fluid-Particle Systems: Recent Research and Development, Ed. Hamid Arastoopour, AIChE Symposium Series, 94, (318), pp42-47.

13. Carman, P.C., (1937), "Fluid flow through granular beds", Transactions of the Institution of Chemical Engineers, Volume 15, pp 150-166.

14. Tallon, S., Davies, C.E., Kirkegaard, M., (2003), "An acoustic method for in-line particle size measurement in flowing bulk solids", Journal of Process mechanical engineering, ImechE, Vol 217, Part E, pp 33-39.

15. Tallon, S., Davies, C.E., Wypych, O., Hastie, D., (2001), "Flow rate measurement in pneumatic conveying pipelines with an audio frequency acoustic meter", Proceedings of the seventh international conference on bulk materials storage, handling and transportation, Newcastle, Australia, October 3rd to 5th, pp 761-771, Volume 2, Ed., Jones, M., The institution of engineers, Australia.

16. Webster, E. S., Davies, C. E., "Determination of Bulk Density and Fill Fraction of Dry Particulate solids Using Helmholtz Resonance", SCENZ Conference, Hamilton, New Zealand, 20 October, 2008.