IMTC 2004 – Instrumentation and Measurement
Technology Conference
Como, Italy, 18-20 May 2004

An Instrumentation System Using Combined Sensing Strategies for On-Line Mass Flow Rate Measurement and Particle Sizing

Robert M. Carter, Yong Yan
Centre for Advanced Instrumentation and Control, University of Greenwich,
Chatham Maritime, Kent. ME4 4TB, UK
Phone: +44 (0)1634 883732, Fax: +44 (0)1634 883153, Email: y.yan@gre.ac.uk

Abstract *– On-line, concurrent measurement of mass flow rate and size distribution of particles in a pneumatic suspension is desirable in many industries. This paper presents the basic principle of and initial results from a novel instrumentation system that uses a combination of electrostatic and digital imaging based sensors in order to achieve these goals. An inferential approach is adopted for the mass flow measurement of particles where velocity and volumetric concentration of particles are measured independently. The velocity of particles is determined by cross correlating two signals derived from a pair of electrostatic sensors, whilst the volumetric concentration of particles is obtained from a digital imaging sensor. The imaging sensor also provides particle size distribution data. Results obtained from a pneumatic conveyor system are presented which show good performance of the system for both mass flow metering (accurate to about ±4%) and particle sizing (reliable to around ±0.5%). A particle size distribution result is also included and the insensitivity of particle sizing to changes in velocity and concentration is assessed. In general, the results obtained are encouraging and the system shows great promise.*

Keywords *– pneumatic conveying, particulate flow, particle size, mass flow rate, electrostatic sensors, digital imaging*

I. INTRODUCTION

Pneumatic conveyance of particulate materials is an important technique used widely in many industries. In order for pneumatic conveying systems to achieve their full potential it is necessary to measure the parameters of the flow without affecting the flow in any way. Much research work has been carried out in the field of particulate flow metering [1] and a wide range of techniques have been developed [2]. Instruments based on these techniques are designed to measure various flow parameters but few of them can measure absolute mass flow rate of particles and/or particle size distribution on an on-line continuous basis [2, 3].

It is clear that an instrumentation system must be developed that can measure mass flow rate and particle size distribution on-line and that can be installed in a non-intrusive manner (i.e. the sensor does not modify the flow in any way). A novel digital imaging based system capable of measuring particle size distribution and volumetric concentration of particles in the manner required has been developed already [4]. When combined with well established electrostatic velocity metering technology [5], it is possible to derive absolute mass flow rate information. Whilst the volumetric concentration of particles is measured by the imaging sensor and the velocity of particles derived from the electrostatic instrument, these two quantities are combined to derive the mass flow rate. This paper presents the basic concepts of both sensing techniques (details have been presented in other publications [4,5]) along with experimental results demonstrating the effectiveness of the methodology.

The work presented, in its present form, uses a novel, complimentary, combination of proven and cost-effective sensing methodologies. It is the intention to develop a system that is worth more than the sum of its parts. Electrostatic sensors, whilst offering proven reliability for velocity measurement, are unsuitable for absolute measurement of volumetric concentration due to the high unpredictability of the magnitude of electrostatic charge found on the particles. An imaging based approach, on the other hand, is well suited to performing particle sizing and concentration measurements. Whilst the measurement of particle velocity is possible with PIV type approaches, these systems use a different sensing arrangement to the present system. It is more cost effective to use electrostatic sensing for velocity measurement than it would be to combine imaging based concentration measurement with PIV and, in any case, PIV provides localized, rather than the required cross sectional, velocity information.

II. SYSTEM DESCRPITION

The system consists of a novel combination of sensor types. These sensors will be explained individually in the interests of clarity.

A. Digital imaging sensor

Particles flowing through a pipeline can be illuminated using a laser sheet to highlight a 'slice' through the flow. Images of that slice can be acquired using a CCD camera. The basic concept and sensing arrangement are illustrated in figure 1. Once the images have been obtained, digital image processing techniques can be applied to extract information such as particle size distribution and absolute solids concentration. Such a system has been found capable, in its present form, of achieving a basic accuracy of ±1.5% when used with particles in the 150μm to 25mm range [4].

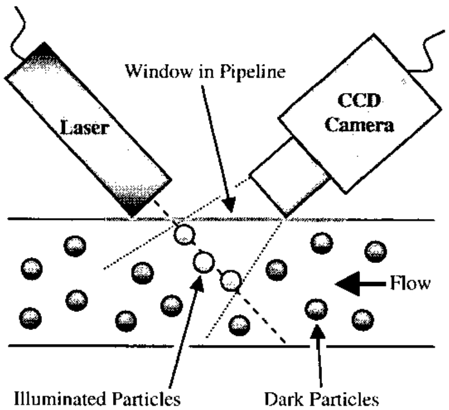

Fig. 1. General imaging sensor arrangement

B. Electrostatic sensor

The movement of particles in a pneumatic pipeline generates a net electrostatic charge on the particles due to various collisions and friction [5]. Although the amount of charge carried on particles is usually unpredictable, the dynamic variation of charge can be detected through the use of an electrode, electrically insulated from the duct, and a suitable signal processing circuit. As the charged particles move past the electrode, a constantly changing electrical signal is observed. If two signals are acquired from a pair of axially spaced circular electrodes that are a known distance apart, then the velocity of particles can be derived through cross correlation between the two signals [1]. The general concept is illustrated in figure 2. Extensive evaluation of such a system has established its high repeatability, good linearity and fast response time [5].

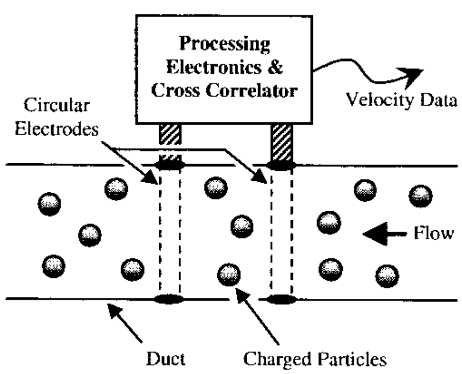

Fig. 2. General electrostatic sensor arrangement

C. Combined sensors

Since the velocity and volumetric concentration of particles are known, these quantities may now be combined, thus allowing the mass flow rate to be deduced. This is expressed, mathematically in equation 1.

$$q_m(t) = A\rho_t V(t)\beta(t) \qquad (1)$$

Where, q_m is the mass flow rate of particle (kg/s), ρ_t is the true density of particles (kg/m^3), V is the velocity of particles (m/s), β is the volumetric concentration of particles (%), A is the cross-sectional area of the duct (m^2), and t is time.

A small flow loop has been set up for evaluation purposes. This is illustrated in figure 3.

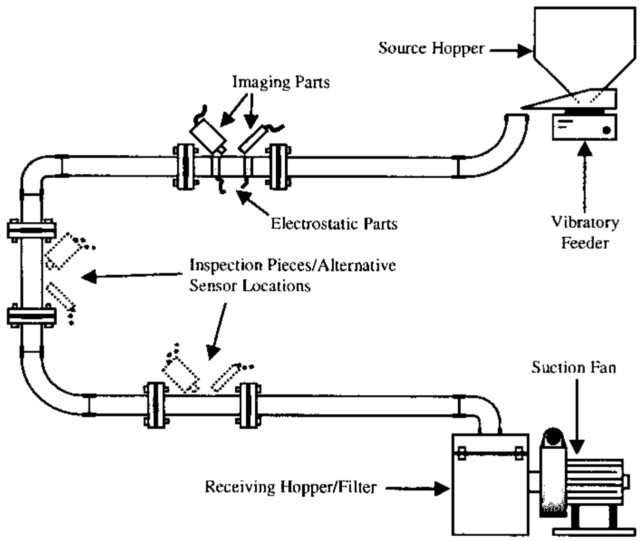

Fig. 3. Layout of test loop

III. RESULTS

In order to evaluate the system laboratory tests have been carried out using table salt as a test material. Salt is clean, free flowing and has well defined absolute density [6] (it should be noted that many table salts have anti-caking additives that improve their usefulness in salt cellars but may affect the absolute material density – for the present work care was taken to find an additive free organic salt). Typical examples of results obtained are shown here.

Figure 4 shows real against measured mass flow rate. Several different velocities are used – the range 10-20m/s represents the typical range of velocities likely to be found in pneumatic conveying (there are, of course, exceptions but these limits offer good coverage of the velocities found in industry). It can be seen from this figure that linearity is excellent.

It should be noted that the range of mass flow rates used here was limited at the high end by the optical sensor – which is only suitable for dilute phase flows with volumetric solids concentrations (β_s) of up to about 2-3% [4] – and at the low end by limitations of the current test set-up.

In general most of the relative errors lie within about ±4-5% which can be seen more clearly in figure 5. These errors display a random distribution and cannot be correlated with increasing velocity. This shows that, within the range of concentrations presented, the system is insensitive to changes in velocity.

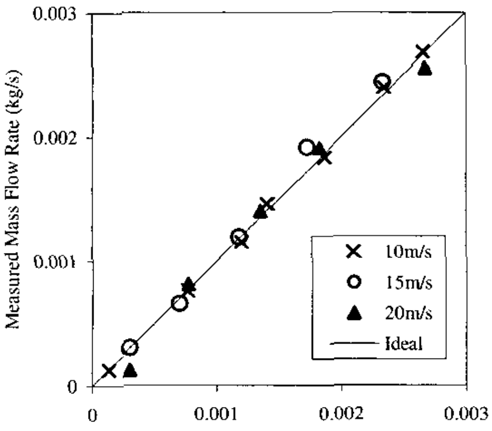

Fig. 4. Mass flow rate results

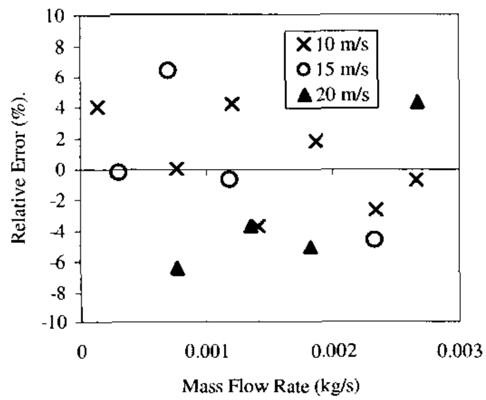

Fig. 5. Relative error of mass flow rate measurement

Mass flow measurement is only one aspect of the current systems usefulness – the imaging sensor is capable of providing important particle sizing information. In order to assess the insensitivity of particle size measurement to changes in concentration and velocity it was necessary to know the actual mean size of the material in question. Figure 6 shows a reference size distribution result generated by the system under known reliable conditions [4] (it is known that this result is comparable closely with those generated by accepted off-line particle sizing solutions). It can be seen that the peak size lies between 355μm and 425μm (the size ranges used here represent widely used industrial sieve sizes). Although not shown on this graph the system also produces a mean size result – in this case a value of 410μm was recorded which lies within the peak size range. 410μm was, therefore, used as a reference against which results generated at varying velocities and concentrations could be compared.

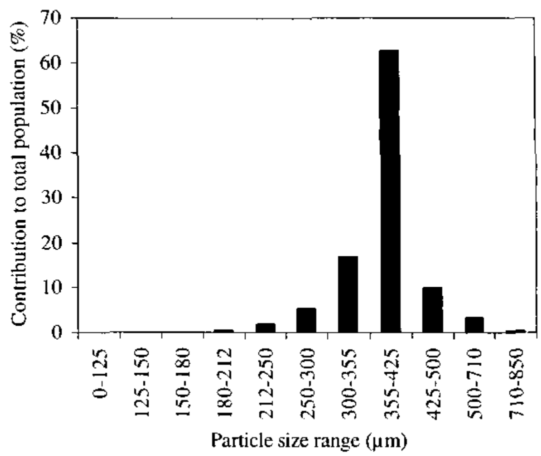

Fig. 6. Particle size distribution result

The results from the concentration and velocity dependence tests are shown in figure 7. Due to practical constraints in relation to the current physical set up the 15m/s velocity point is not shown here but the range of 10-20m/s is still represented.

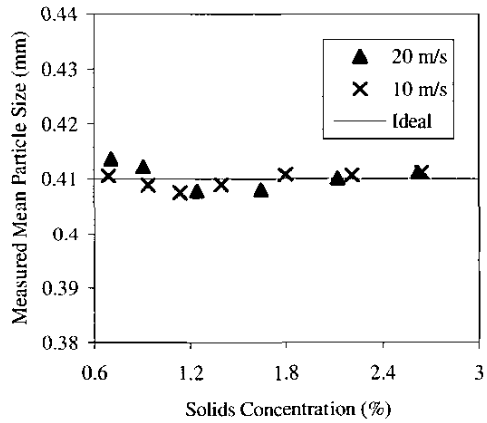

Fig. 7. Particle size results

It can be seen that the results are encouraging – the expected mean size is observed throughout all measurements. Relative errors all lie within ±1% and most are within ±0.5%. The errors can be seen more clearly in figure 8 where it is clear that there is no correlation with velocity or concentration – the errors are random. The results indicate that, within the given range of conditions the system can measure particle size irrespective of concentration and velocity.

Figure 9 shows a typical live flow image of salt flowing through the test loop – the image depicts a mass flow rate of about 0.0015kg/s at a velocity of 10m/s. It is interesting to note that, even with such a small number of particles in just one image a good range of sizes are visible. When the system operates on-line the results from many frames may be averaged allowing very large numbers of particles to contribute towards the end result. This helps to ensure the representativeness of the sizing data [7].

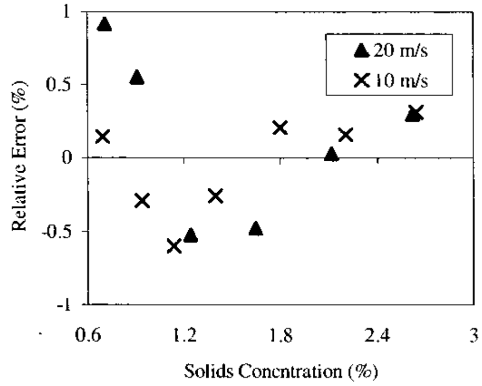

Fig. 8. Relative error of particle size measurement

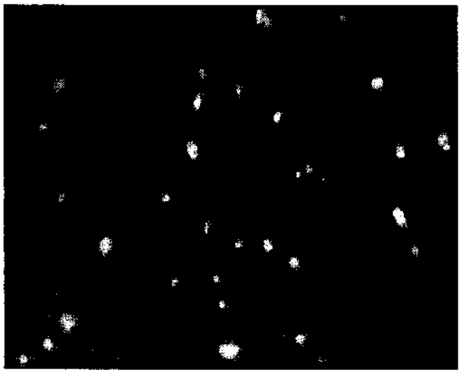

Fig. 9. Typical flow image

IV. CONCLUSIONS

This paper has presented the concept and capabilities of a novel combination of sensor types intended to measure, on an on-line and non-intrusive basis, the absolute mass flow rate and size distribution of particulate materials in pneumatic conveyance. It is usable at concentrations up to 2-3% and achieves typical measurement accuracies of ±4% and ±0.5% for mass flow rate and sizing, respectively. It is believed that continued work will improve the accuracy still further. With the ever increasing power of modern PCs image processing techniques become more and more attractive and cost-effective. The current system combines low cost electrostatic measurement with the potential benefits of image processing to produce a versatile and cost-effective system. The potential benefits to industry of such a system are clear and it has been shown that the combination of existing techniques can result in a system that is worth more than the sum of its parts.

ACKNOWLEDGEMENT

The Authors wish to thank the British Coal Utilization Research Association (BCURA) and Innogy plc for providing funding and certain test facilities used during this work.

REFERENCES

[1] Y. Yan and D. Stewart, "Guide to the Flow Measurement of Particulate Solids in Pipelines". The Institute of Measurement and Control, London 2001.

[2] Y. Yan, "Mass Flow Measurement of Bulk Solids in Pneumatic Pipelines". *Meas. Sci. Technol.*, Vol. 7, pp. 1687-1706, 1996.

[3] M. Pohl, "Particle Sizing Moves from the Lab to the Process". *PBE International*, pp. 25-31, May 2001.

[4] R. M. Carter and Y. Yan, "On-line Particle Sizing of Pulverised and Granular Fuels using Digital Imaging Techniques". *Meas. Sci. Technol.*, Vol. 14, pp. 1099-1109, 2003.

[5] J. Ma and Y. Yan, "Design and Evaluation of Electrostatic Sensors for the Mass Flow Measurement of Pneumatically Conveyed Solids". *Flow Measurement and Instrumentation*, Vol. 11, No. 3, pp. 195-204, 2000.

[6] The Salt Institute, http://www.saltinstitute.org/

[7] H. Masuda and K. Gotoh, "Study on the Sample Size Required for the Estimation of Mean Particle Diameter". *Advanced powder technology*, Vol. 10, pp. 159-173, 1998.