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Title: Measurement of Velocity and Concentration Profiles of Pneumatically Conveyed Particles using an Electrostatic Sensor Array

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ABSTRACT

The ability to monitor the velocity and concentration profiles for the whole diameter of a pipe would allow the complex flow dynamics associated with particles in a pneumatic suspension to be measured. This paper presents a method of online monitoring of the particle velocity and particle concentration for the whole diameter of the pipe for a pneumatic bulk solid conveying system. This is achieved by using an array structure of five electrostatic sensors across the whole diameter of the pipe to measure the particle velocity and concentration profiles. Experimental tests were carried out on a laboratory-scale test rig over a range of particle velocities. Results show that the electrostatic sensor array is capable of measuring the multiple velocities and concentrations that occur across the diameter of a pneumatic conveying pipe. Through analysis of velocity and correlation coefficient data different parts of the pipe diameter such as those along the pipe wall are determined to have more turbulence then the flow at the centre of the pipe.

Index Terms - pulverized fuel; velocity profile; concentration profile; mass flow rate; electrostatic sensor; sensor array

I. INTRODUCTION

Dilute gas-solid transport systems are used in a variety of industries such as chemical, steel and energy. The concentration of solids in dilute gas-solid flow is less than 0.1% by volume, which presents a well-known measurement challenge [1]. Being able to monitor the velocity profile and particle concentration for the whole diameter of the pipe would allow the mass flow rate to be accurately monitored and achieve an in-depth understanding of gas-solid two-phase flows allowing comparison and validation to be made between practical experiments and computational fluid dynamic (CFD) simulations.

Nowhere is this more important than in the energy industry where accurately monitoring the mass flow rate of the fuel is important in improving burning efficiency and reducing slagging and emissions. Now that many coal fired power plants across the world are being converted to co-firing with a mixture biomass or 100% biomass fuelling to increase the amount of renewable energy generated, the particle flow dynamics inside the pipe have become more complex due to the irregular shape and generally wider size range biomass particles.

To this end a diverse range of sensor paradigms have been developed and proposed to monitor particle velocity and concentration in a bulk solid pneumatic conveying system; these include capacitive [2-6], radiometric [7], optical [8-11], acoustic/ultrasonic [12], microwave [13] and heat transfer method [14]. All of these types of sensors have the advantage of being nonintrusive and capable of monitoring both particle velocity and concentration. However capacitive sensors are susceptible to moisture which can affect the dielectric properties of the material being monitored [6]. Radiometric sensors have the drawbacks that they contain a radioactive material and their use is governed by administratively inconvenient health and safety regulations. Optical sensors have the shortcoming that they require a transparent window in the pipe which is susceptible to contamination and abrasion by the pulverised material. Nonetheless, this drawback can be addressed by using an air purging system to reduce contamination [10]. Acoustic/ultrasonic sensors are susceptible to false signals that can result in error and the optimum frequency is linked to particle size distribution [15]. Microwave sensors have the disadvantage that they have a moderate accuracy and relatively high cost [13]. The heat transfer method is mainly suited for dense-phase flow measurement [14]. However electrostatic sensors due to their robustness and low cost have the advantage over other sensors. There are three main designs of electrodes used for electrostatic sensors: ring, arc and probe electrodes [11, 16-19].

Ring electrodes are constructed within the pipe wall and because of this have the advantage of being completely non-invasive since they do not impede the particle flow in the pipe. They do, however, have disadvantages in that they are more sensitive to particles in close proximity to the pipe wall [16]. Then again when ring electrodes are used to measure the particle velocity in a multi-phase flow using the cross-correlation method this will reduce the quality of the correlation coefficient between the upstream and downstream because different parts of the particle flow in the pipe cross section will be traveling at different velocities [16]. Particle velocity has also been determined using ring electrodes in a linear array configuration. Xu et al. [17] used a linear electrostatic sensor array to determine particle velocity using the spatial filtering method. It was determined through experimentation and finite element modelling (FEM) that the optimum number of electrodes should be between 4 and 10. It was also suggested that the ratio between the electrode spacing compared to the electrode width should be between 7 and 10, and the of the electrode width to pipe radius should be in the range of 0.1-0.2.

Probe electrodes differ from ring and arc electrodes in that they have the disadvantage that they are an invasive sensor technology. However, in dilute-phase flow this does not cause a significant problem due to the very low particle concentration. Also the small cross sectional area of the probe electrodes mean that they obstruct a small proportion of the pipe cross section. Shao et al. [16] investigated this type of electrostatic sensor through a combination of practical online experimentation and offline finite element modelling. One of the design aspects of the probe electrodes was the optimum depth of the probe. It was discovered that a probe depth of 0.3-0.5 of the pipe diameter would give a realistic approximation of the average particle velocity. Shao et al. [16] also compared the probe electrode to the ring electrode and found that using the cross correlation method to determine particle velocity the probe electrode had a higher correlation coefficient (around 0.55-0.75) compared to the ring electrode (around 0.35-0.5) [16].

The basic design of the electrostatic sensor array along with preliminary experimental results was reported at the 2015 IEEE International Instrumentation and Measurement Technology Conference [20]. This extended version of the paper presents in detail the design considerations, construction and systematic assessment of the sensor array that were not covered in [20] and [21].

Electrostatic sensors have also been applied to measure the volumetric concentrations of the particles inside the pipe as presented by Yan et al. [22]. The principle of using electrostatic sensors to determine particle concentration is that as the particle concentration increases so does the magnitude of the electrostatic charge. Since the electrostatic sensors are designed to detect moving particles the level of the charge is determined my measuring the magnitude of the change in the signal [22]. However, Yan [23] discusses that there are limitations to using electrostatic sensors to determine particle concentration in that the electrostatic signal is affected by particle variables such as: particle size; how long the conveyed particles have had to pre-charge; and dielectric properties of the material being conveyed. Moreover, the environment inside the pipe, such as temperature and humidity, can be a factor. This paper presents an in depth design and implementation of an electrostatic sensor array that is capable of measuring the particle flow dynamics that occur in the pipe that previous electrostatic sensors (ring [16-18], arc [18] and probe [16]) were unable to achieve.

II. MEASUREMENT PRINCIPLE

An often unwanted phenomenon of pneumatic conveying systems (for safety reasons) is that as solid particles are conveyed down a pipe they pick up electrostatic charge [24]. The level and distribution of this charge is random due to the nature of how it is generated inside the pipe through interaction and friction between the air and other particles [24]. Using an electrostatic sensor the charge carried by the particles can be detected as the particles pass the sensor since a small amount of charge is induced on the electrode [25].

The electrostatic sensor consists of an insulated electrode and a signal conditioning circuit that takes the charge induced on the electrode and converts it into a voltage signal that can be digitised by an analogue to digital converter (ADC).

There are two methods to determine particle velocity using electrostatic sensors: the spatial filtering method [17] and the cross correlation method [23]. Since the spatial filtering method uses a linear array of electrodes it was unsuitable for use with the electrostatic sensor array presented in this study due to space constraints on the sensor blade. Using the cross correlation method to measure particle velocity of particles traveling inside the pneumatic conveying pipe involves the use of two electrodes arranged in a configuration as shown in Fig. 1 [25].

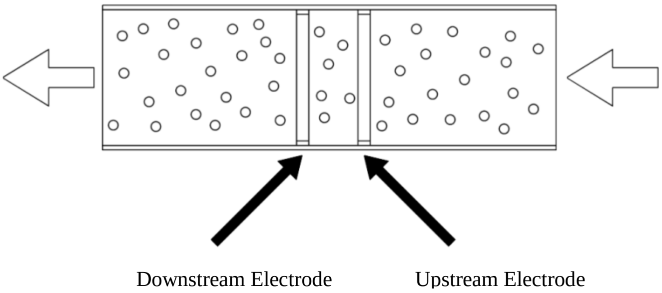

Fig. 1. Electrode configuration inside a pipe

Since the distance between the upstream and downstream electrodes is known, particle velocity (V_c) can be calculated from:

$$V_c = \frac{L}{\tau_m} \quad (1)$$

Where L is the spacing between the upstream and downstream electrodes and τ_m is the time difference between the upstream and downstream signals. To determine τ_m the upstream and downstream signals have to be digitised using an ADC. It is at this point that resolution and sampling rate of the ADC has to be taken into account; the resolution has to be sufficiently high enough to ensure minute changes in the charge picked up from the electrodes can be detected; the sampling rate of the ADC has to ensure that the resolution in the time domain is higher than the possible delay τ_m between the upstream and downstream signals. To determine τ_m the cross-correlation method is used. The delay between the two signals is determined from the location of the dominant peak in the cross correlation function [23]. The cross correlation method in Eq. (2) is used since the cross correlation is carried out on an embedded microcontroller and computational resources are limited.

$$Rxy[m] = \frac{1}{N}\sum_{n=1}^{N} x[n]y[n+m] \tag{2}$$

Where x[n] and y[n] are the digitised signals from the upstream and downstream electrodes respectively shown in Fig. 2. The position of the dominant peak for the resulting correlation function known as the correlation coefficient indicates the delay between the upstream and downstream signals, as illustrated in Fig. 3.

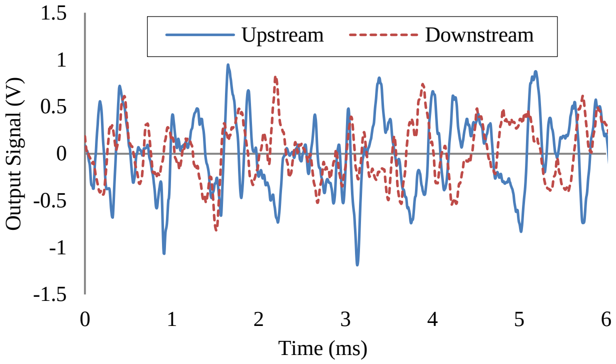

Fig. 2. Upstream and downstream signals from electrostatic sensors

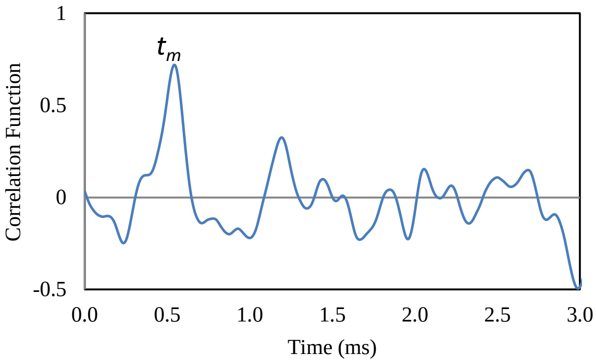

Fig. 3. Correlation function between the upstream and downstream sensor signals

Since the resulting signal from the sensor is random [22] the particle concentration is determined and represented by the magnitude of the r.m.s. (root-mean-square) charge level of the electrostatic signal detected by the electrostatic sensor.

$$V_{rms} = \sqrt{\frac{\sum_{n=1}^{N} x[n]^2}{N}} \tag{3}$$

Where x is the signal from the electrostatic sensor electrode, n is the sample number and N is the total number of samples. Conversely the exact particle concentration cannot be determined via this method due to variables such as particle size, type of particles and particle velocity [23].

III. SENSOR DESIGN

Like the probe electrode design the electrostatic sensor array is an intrusive sensor that comes into contact with the particle flow. However, unlike the probe sensor, the sensor array spans the whole diameter of the pipe and is divided into five pairs of identical electrodes as shown in Fig. 4. Due to the invasive nature of the sensor array design all attempts have been made to reduce the thickness of the sensor which is currently 2.5 mm thick. Each electrode has a width of 1mm and a length of 8 mm and the electrode pairs (upstream/downstream) are set 10 mm apart. The sensor array is a blade design and only has electrodes on one side. The leading edge of the sensor array is a 45° knife edge intended to increase the aerodynamics of the sensor array. In addition, the 45° degree edge deflects most of the turbulence and velocity change caused by the sensor array behind the electrodes as illustrated in Fig. 5. This design of sensor array can be easily adapted for larger size ducting (150mm in diameter and larger) as found in pulverised fuel fired power stations. The use on larger diameter ducting would also allow more elements of the array to be added to increase the resolution of the measured velocity and concentration profiles.

The electrodes are fabricated out of copper and are etched onto printed circuit board (PCB). The preamplifier for the electrostatic sensors is constructed inside the sensor array blade to reduce the connection distance between the electrode and the preamplifier, subsequently reducing unwanted noise. The outer casing of the sensor array blade is fabricated from metal which is earthed to shield the preamplifier from unwanted noise. For practical versions of the electrostatic sensor array the blade and electrodes can be coated with a durable material to improve abrasive resistance. The physical size of the electronics for the preamplifiers was the determining factor of the number of electrodes that could be constructed across the diameter of the pipe. The signal from the preamplifier is then passed through a variable secondary amplifier and an anti-aliasing low pass filter with a cut off frequency of 15 kHz in order to remove high frequency noise. Care was taken during the construction of the entire signal conditioning circuits to ensure each was matched to each other. An analogue multiplexer (MUX) controlled from the microcontroller selects each element of the array. The analogue signal is digitised in an external 12-bit ADC with a sampling rate of 150 kHz (10 times the highest frequency component of the signal) which is mounted near the signal conditioning circuit and is connected to the microcontroller via a serial peripheral interface (SPI) bus. All analogue parts of the signal conditioning circuit are shielded against external noise. The cross correlation processing software is embedded into a 32 bit 100 MHz microcontroller which outputs to a PC as shown in Fig. 6. The microcontroller is capable of calculating the velocity using the cross correlation method for a single pair of electrodes in approximately 100 ms. Consequently the system has a refresh rate for the measurement of the velocity, concentration and correlation coefficient profiles of approximately 0.5 seconds.

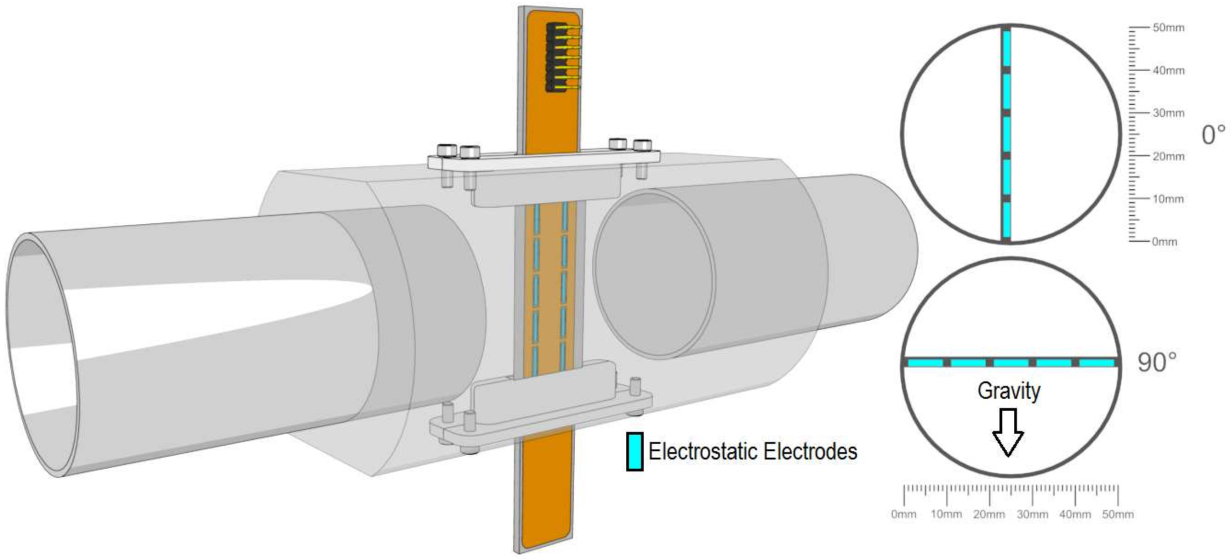

Fig. 4. Electrostatic array mounted inside a pipe spool with pipe cross section diagram

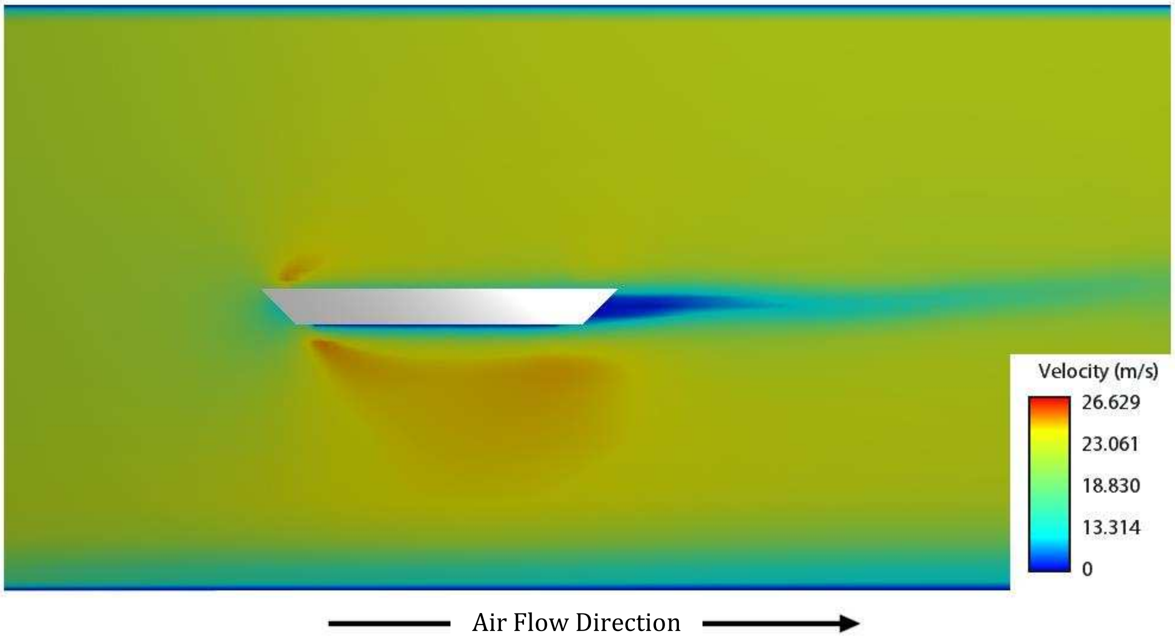

Fig. 5. Wind tunnel simulation of the effect of the sensor array on air velocity

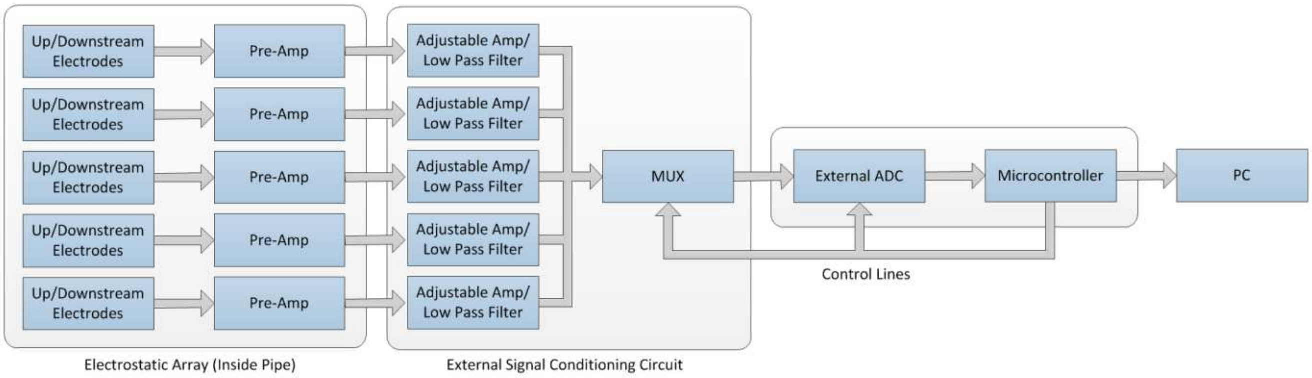

Fig. 6. Block diagram of the electrostatic array sensor based particle measurement system

IV. EXPERIMENTAL SETUP

The sensor array is mounted inside a custom 50mm bore spool piece that allows the sensor array to be rotated around the cross sectional axes shown in Fig. 4. Experiments were carried out using flour in a dilute flow with a flow rate of 1.8 kg/hour on a negative pressure bulk solid conveying test rig (Fig. 7 and Fig. 8). All pipework on the test rig is constructed from stainless steel for abrasive resistance and is grounded for safety. Lack of established standards and traceability in the field of particle flow measurement is one of the challenges researchers have to face when developing techniques to resolve the difficult industrial measurement problems [25]. In the present study air velocity profiles were determined as a reference by using a commercial hot-wire anemometer with readings taken from pipe at the same location of the sensor array. During the experiments, ambient temperature (25.3°C average) and relative humidity (47.5% average) were monitored to ensure environmental test conditions were the same for each test. Experiments were carried out with the sensor array mounted on a horizontal pipe section with the array mounted in two orientations 0° and 90° as shown in Fig. 4. The electrostatic sensor array is mounted 2.6m (52 pipe diameters) from the right angle pipe section on the feeder input to ensure the measurement of a developed flow. Tests were carried out with five different air velocities (reference air velocity measurements taken from the centre of the pipe). After each experiment the filter on the vacuum plant was cleaned to ensure consistency. For each pair of electrodes the cross correlation used 1024 samples on both the upstream and downstream electrodes. A total of 500 velocity, concentration and correlation coefficient readings were taken on each element of the array for each air velocity. It has been observed that particle size and shape have an effect on particle flow stability [21]. In this study particle size and shape (Fig. 9-11) were measured using an in-house particle imager [26]. The particle shape was quantified by measuring the particle aspect ratio (shortest to the longest diameters across the particle). The aspect ratio distribution shown in Fig. 11 indicates that the majority of the flour particles are spherical in shape.

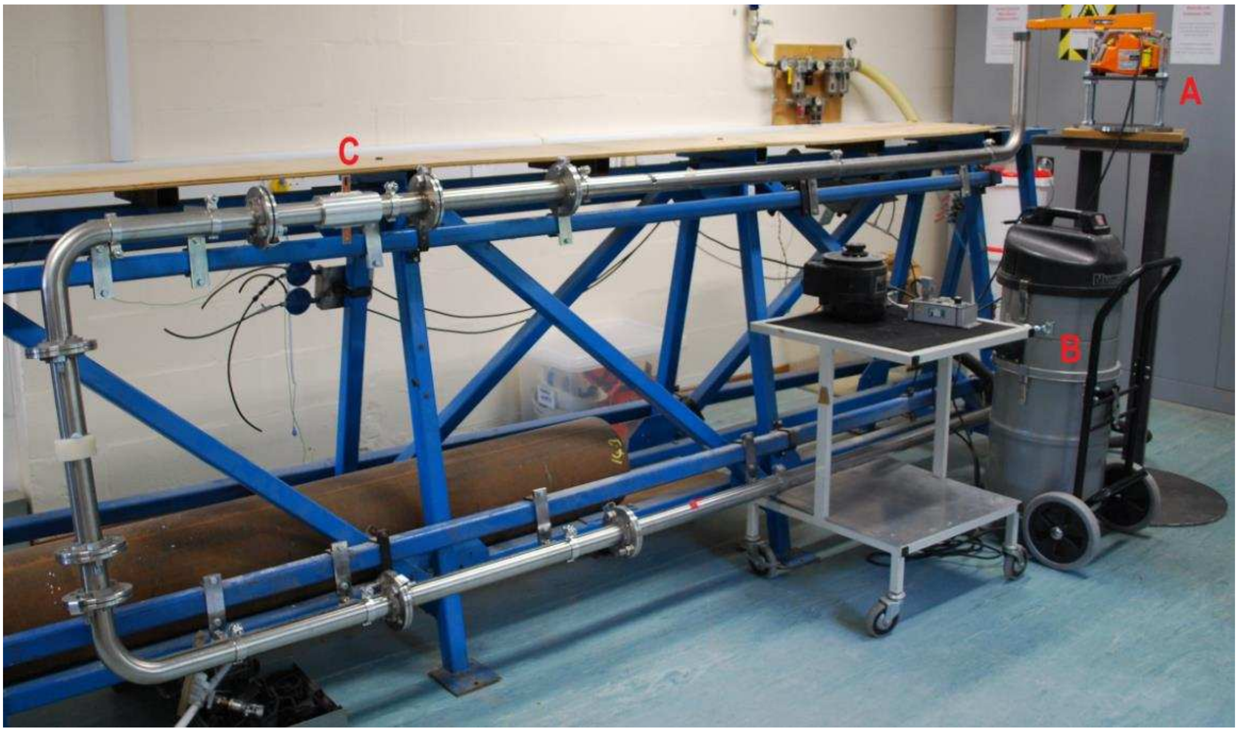

Fig. 7. Photo of the particle flow test rig, (A) vibration feeder, (B) variable vacuum unit, (C) sensor spool

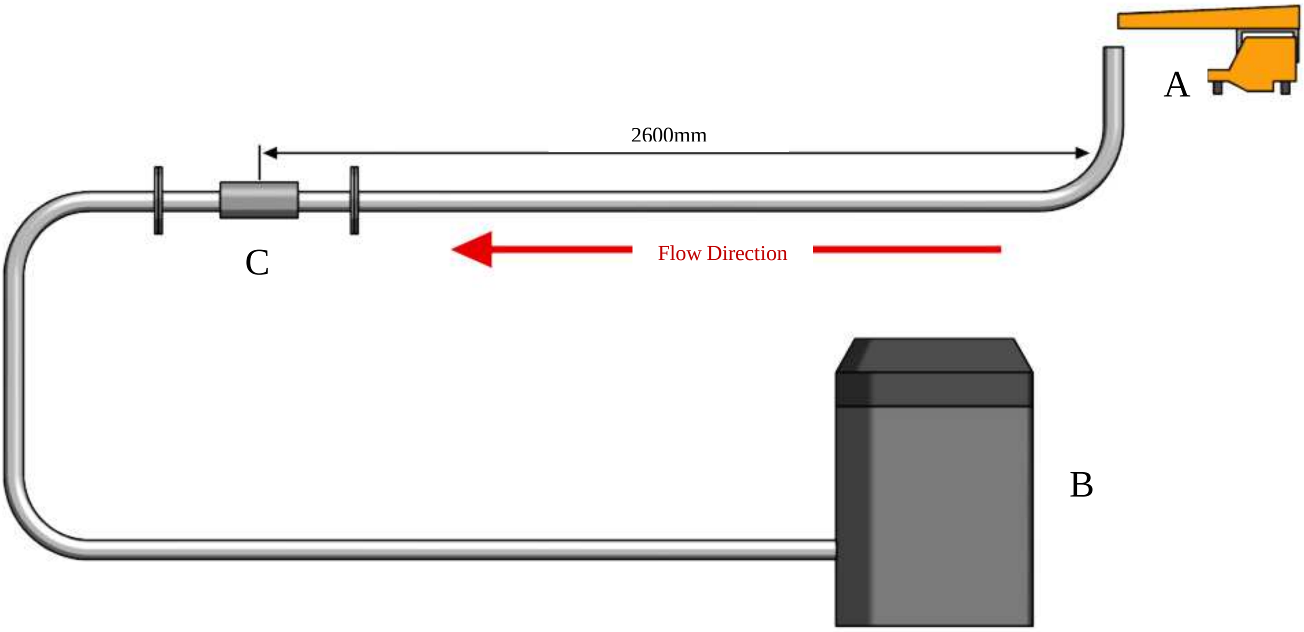

Fig. 8 Layout of particle flow test rig: (A) vibration feeder, (B) variable vacuum unit, (C) sensor spool

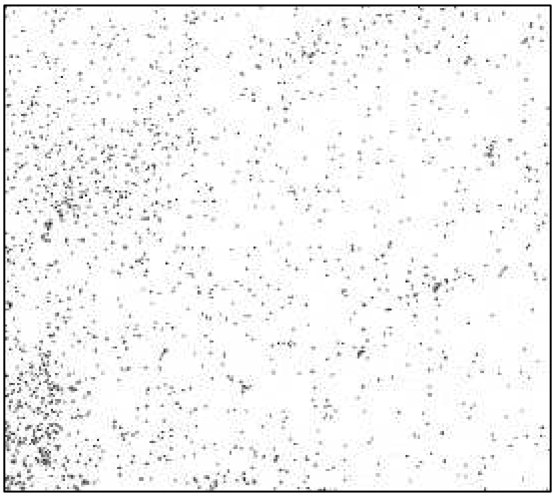

Fig. 9. Scan image of flour particles (not to scale)

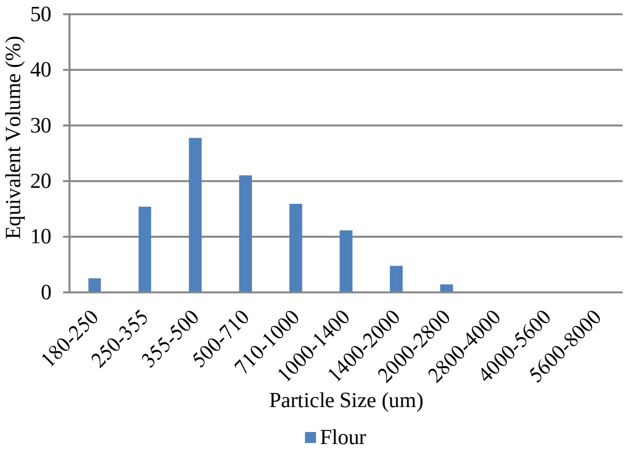

Fig. 10. Particle size distribution of flour particles

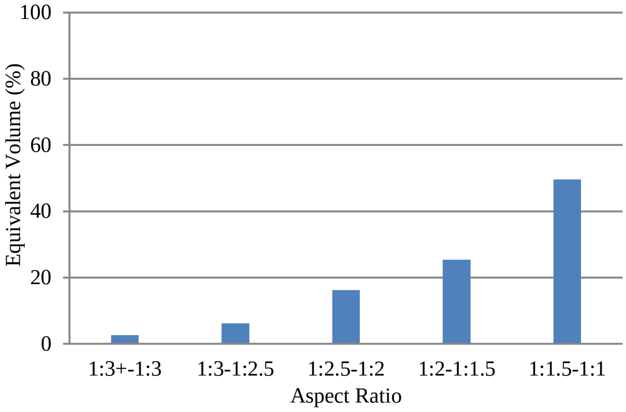

Fig. 11. Aspect ratio distribution of flour particles

V. RESULTS

The sensor array was able to determine the particle velocity and particle concentration for the diameter of the pipe. Fig. 12 and Fig. 13 show the mean velocity profile for a range of air velocities (20.3-24.3 m/s). The profiles clearly show that particles traveling at the centre of the pipe are moving at a higher velocity then those moving along the pipe wall due to the frictional force acting on the conveying air and particles caused by interaction with the pipe wall. The 0° velocity profile in Fig. 12 shows that the velocity at the bottom of the pipe (5 mm) is lower than the velocity at the top of the pipe (45 mm); this is due to gravity's effect on the particles forcing them to come into contact with the pipe wall at the bottom of the pipe. Whereas Fig. 13 shows the velocity profile for 90° which is more symmetrical compared to 0° since gravity is having a uniform effect over the whole diameter. Fig. 14 and Fig. 15 show the air velocity profiles as measured using a commercial hot-wire anemometer in both 0° and 90° orientations. Fig. 16 illustrates particle velocity compared to the conveying air velocity at the centre of the pipe. As expected, Fig. 14-16 show that the particle velocity is lower than the conveying air velocity. A detailed comparison of the particle and air velocity profiles, as shown in Fig. 17 and Fig. 18, illustrates that the difference between the particle and air velocities decreases for higher air velocities, indicating that higher air velocities are better at keeping the particles in a suspension. The reason for the difference between the conveying air velocity and particle velocity is because the process of conveying and suspending the particles is one of drag force and hence the particle velocity will be lower than the conveying air [24]. Typically in a horizontal pipe the particle velocity is 80% of the conveying air velocity. However, this value can vary depending on parameters such as particle size, shape and density [24]. Conversely, the effect of friction between the pipe wall and particle flow can be seen in Fig. 17 and Fig. 18 where the difference between the particle and air velocities is higher at 5 mm and 45 mm (however, this observation only holds true at higher air velocities, at lower air velocities 20.3 m/s and 21.4 m/s has a more uniform profile since the particles may not be fully suspended). The effect of gravity can be seen in Fig. 17 where the difference between the air velocity and the particle velocity is higher the closer to the bottom of the pipe.

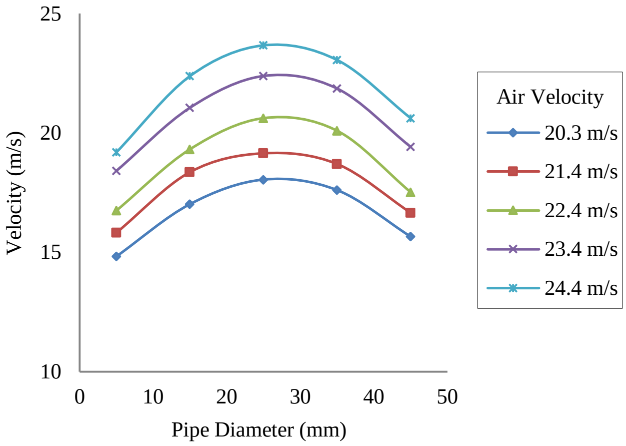

Fig. 12. Mean velocity profile measured by the sensor array at 0° (data points indicate centre of the electrode)

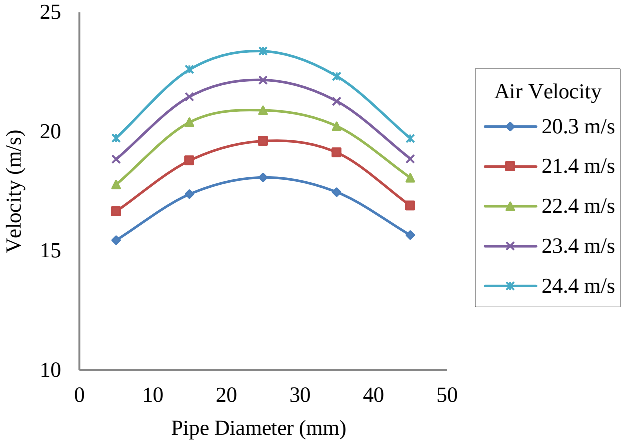

Fig. 13. Mean velocity profile measured by the sensor array at 90°

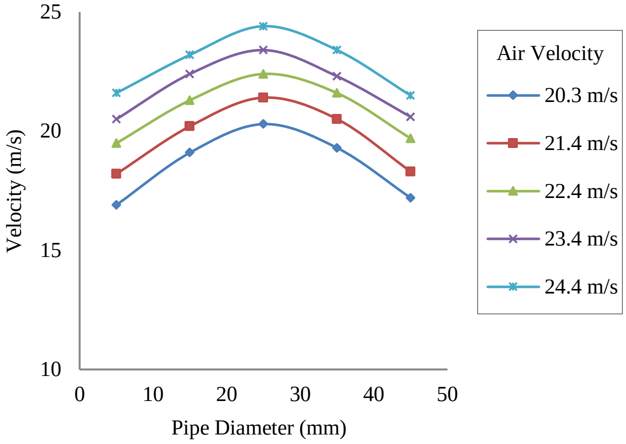

Fig. 14. Air velocity profiles measured using a hot-wire anemometer for the sensor array at 0°

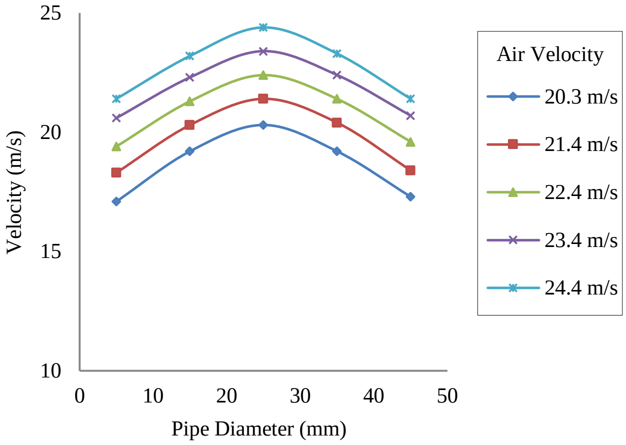

Fig. 15. Air velocity profiles measured using a hot-wire anemometer for the sensor array at 90°

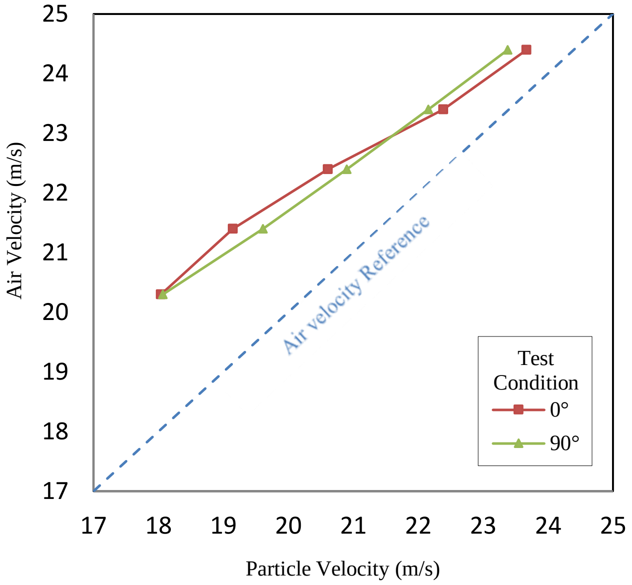

Fig. 16. Air velocity compared to particle velocity at the centre of the pipe

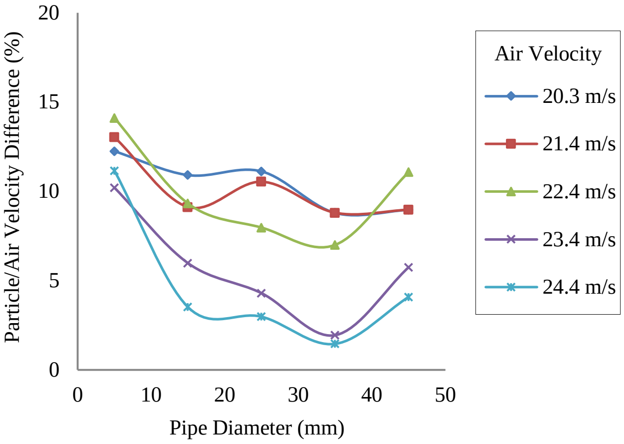

Fig. 17. Percentage difference between the air and particle velocity profiles for the sensor array at 0°

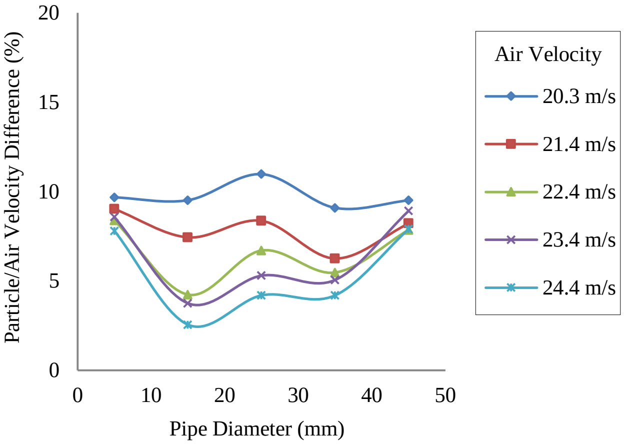

Fig. 18. Percentage difference between the air and particle velocity profiles for the sensor array at 90°

The normalised velocity standard deviation profile shown in Fig. 19 and Fig. 20 shows that the particle velocities measured in the centre of the pipe have a lower deviation compared to those along the pipe wall indicating a more stable particle flow in the centre of the pipe. This result is consistent with previous investigations carried out using pulverised biomass by [21]

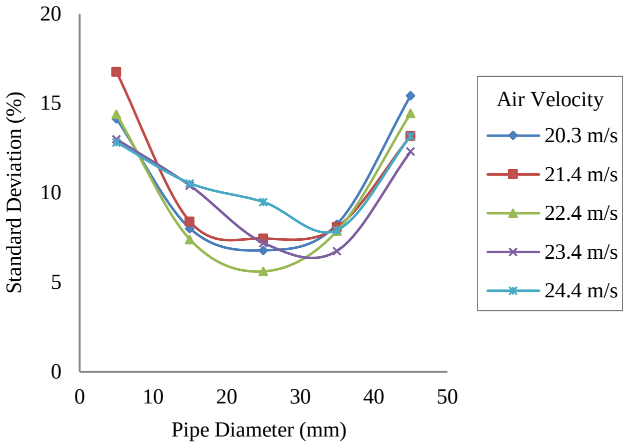

Fig. 19. Normalised standard deviation profile of the velocities measured by the electrostatic array sensor at 0°

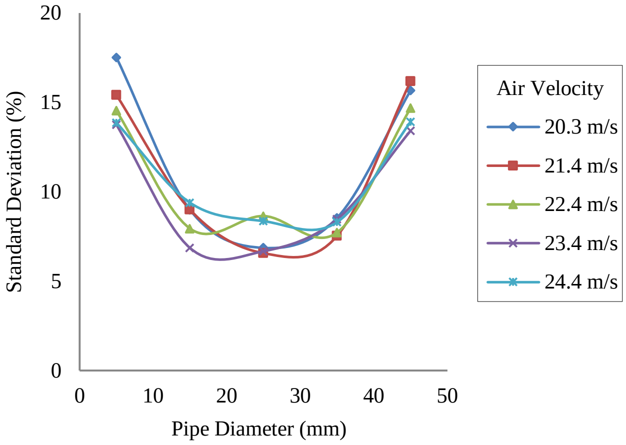

Fig. 20. Normalised standard deviation profile of the velocities measured by the electrostatic array sensor at 90°

The particle concentration shown in Fig. 21 shows that the concentration increases the closer to the bottom of the pipe due to the effect of gravity. However, at the very bottom of the pipe (5 mm) the particle concentration is less than that measured on the sensor element above (15 mm). Similar experimentation carried out using different particle sizes of pulverised biomass [21] does not encounter this phenomenon. A possible reason for this is that the particle size of the flour used in this experiment is smaller than the willow biomass particles [21], as shown in Fig. 9-11. The smaller flour particles would have a lower mass then the larger biomass particles and would therefore be affected more by the turbulence caused by the proximity of the sensor blade and the pipe wall. This turbulence would mean the smaller particles would be unable to enter the smaller volume of space at the bottom of the pipe between the sensor blade and pipe wall thus causing less particles to be detected by the sensor. However, for larger pipe bores this effect would be less dramatic since the pipe radius would be increased. The phenomenon of reduced particle concentration along the pipe wall can be seen on the 90° particle concentration profile (Fig. 22), which shows that the concentration in the centre of the pipe is higher than along the pipe wall. Another possibility is that smaller particles are affected more by the discharging effect of coming into contact with the pipe wall due to the steel pipe being earthed for safety reasons. Fig. 22 also shows that for the higher air velocities (22.4-24.4m/s) the r.m.s charge is increasing in the centre of the pipe (with exception to the r.m.s. measured at the centre of the pipe for 24.4 m/s. This is most likely due to a disruption of the particle input on the vibration feeder since it does not appear under other air velocity conditions). This is feasibly due to the fact that at higher air velocities more particles are being suspended. Consequently more particles are able to be detected by the sensor array in the 90° orientation.

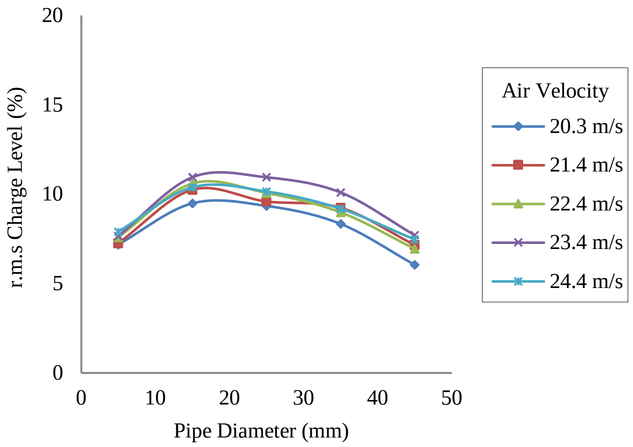

Fig. 21. Mean particle concentration profile using normalised r.m.s. charge value to measure particle concentration at 0°

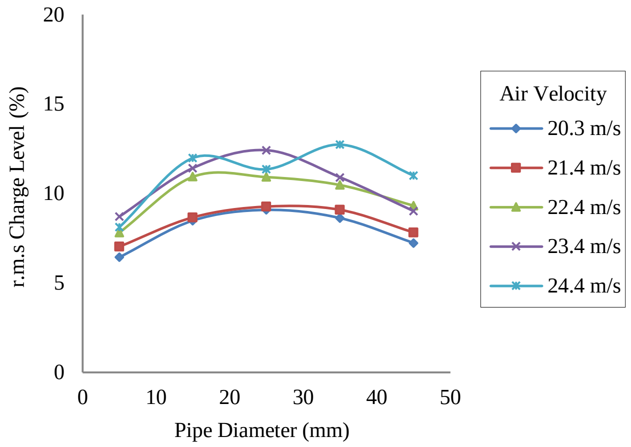

Fig. 22. Mean particle concentration profile using normalised r.m.s. charge value to measure particle concentration at 90°

The magnitude of the correlation coefficient is an indication of the stability of the particle flow [18] (the closer to 1 the correlation coefficient is, the more stable the flow). Fig. 23 and Fig. 24 show the correlation coefficient profiles (0° and 90° respectively). For the pipe diameter, it is clear that the correlation coefficient is higher in the centre of the pipe compared to that along the pipe wall, demonstrating that the particle flow is more stable in the centre of the pipe which is consistent over all five air velocities.

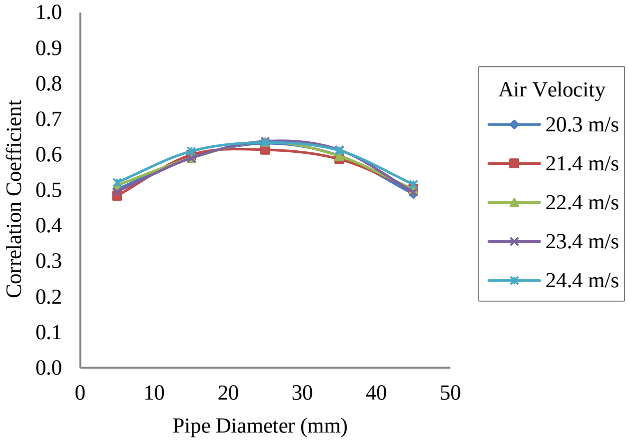

Fig. 23. Mean correlation coefficient profile for the pipe cross section at 0°

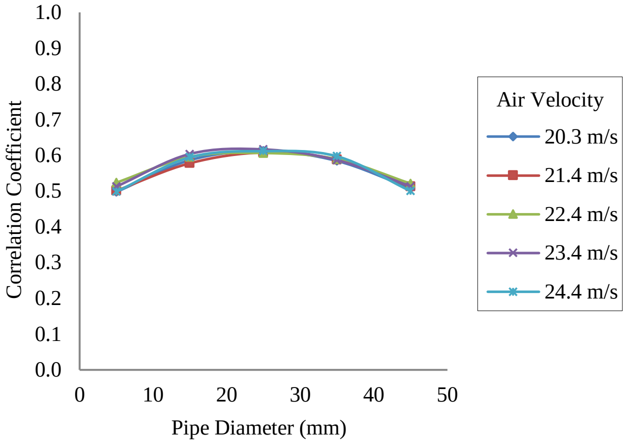

Fig. 24. Mean correlation coefficient profile for the pipe cross section at 90°

The normalised standard deviation of the correlation coefficient with the sensor array in the 0° orientation shown in Fig. 25 agrees well with the standard deviation of the velocity in the same orientation (Fig. 19); with the correlation coefficient deviating less in the centre of the pipe compared to along the pipe wall. However, the normalised standard deviation of the correlation coefficient with the sensor array in the 90° orientation (Fig. 26) does not agree with the standard deviation of the velocity in the 90° orientation (Fig. 20). The normalised standard deviation shows that the correlation coefficient deviated more evenly over the pipe diameter with only a small reduction of the deviation in the centre of the pipe. This effect is not fully understood. Previous work [21] using fine pulverised biomass with the electrostatic sensor array in the 90° orientation on a horizontal pipe showed significantly less deviation in the centre of the pipe. This is possibly an indication that a combination of turbulence (caused by the sensor array interacting with the particle flow), a smaller particle size/mass and gravity (since gravity is having a uniform effect) has a significant effect on the standard deviation of the correlation coefficient on a horizontal pipe at 90° orientation.

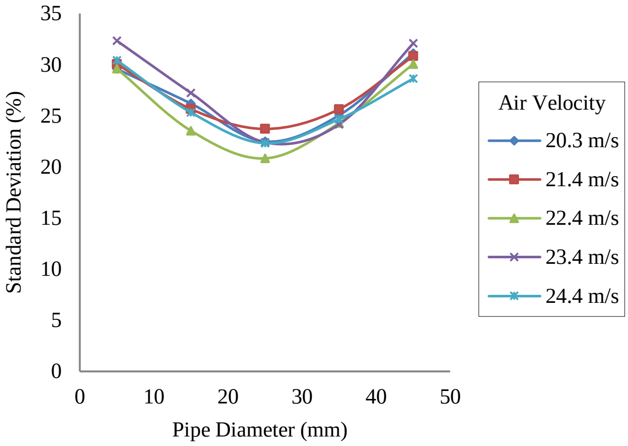

Fig. 25. Normalised standard deviation profile of the correlation coefficient measured by the electrostatic array sensor at 0°

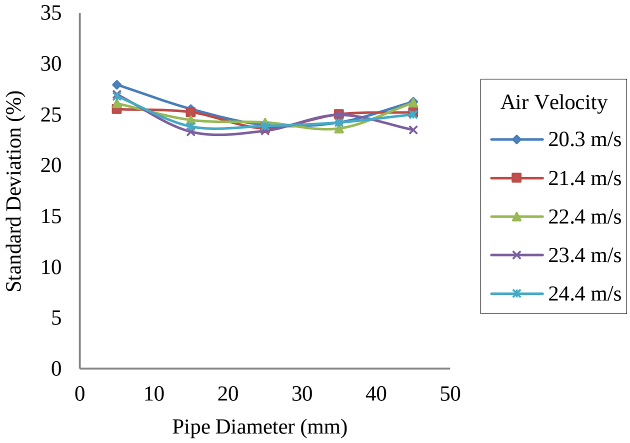

Fig. 26. Normalised standard deviation profile of the correlation coefficient measured by the electrostatic array sensor at 90°

VI. CONCLUSIONS

An electrostatic sensor array has been designed, constructed and tested that is capable of monitoring the particle velocity and concentration profiles for the diameter of a pneumatic conveying pipe. The sensor array comprises of five independent electrostatic sensing elements across the whole diameter of the pipe. Through analysis of the velocity profiles as well as correlation coefficient profiles the performance of the electrostatic sensor array is in line with particle flow dynamics inside a pipe. It has been found that the particle flow in the centre of the pipe being more stable than the particle flow along the pipe wall. A direct comparison between the air velocity profile (measured using a hot-wire anemometer) and the particle velocity profile (measured using the electrostatic sensor array) has shown that interaction with the pipe wall results in velocity loss in the conveyed particles due to friction. The effect of gravity has also been observed on a horizontal pipe since particles at the bottom of the pipe move slower than those on the top of the pipe.

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