*XVII IMEKO World Congress*
*Metrology in the 3rd Millennium*
*June 22–27, 2003, Dubrovnik, Croatia*

# MEASUREMENT OF VELOCITY AND MASS FLOW OF POWDERS

*Anton Fuchs, Bernhard Brandstätter, Bernhard Schweighofer, and Georg Brasseur*

Institute of Electrical Measurement and Measurement Signal Processing, Graz University of Technology, Austria
Kopernikusgasse 24/IV, A-8010 Graz, Austria

**Abstract** – In this paper a cost-effective method for measuring transportation velocity and the velocity profile of a material flow of powdery solids inside a pipe is presented. For the measurement, artificial perturbations are brought into the mass flow and the effects of these perturbations are acquired and correlated at measurement sections. The velocity profile is calculated with the knowledge of the perturbation's rheological decomposition and the sensitivity distribution of the measurement configuration.

**Keywords** – powder mass flow, velocity profile

## 1. INTRODUCTION

For pneumatically conveyed amorphous solids, mass flow measurement is normally ascribed to the imprecise and interrupted measurement of weight or volume. Due to possibly high transport velocities and a fraction of quartz and other rough components, a non-invasive measurement principle is required. For most applications one has to emanate from non-conducting amorphous solids in a nearly homogenous flow. Dry cement powder has been chosen as an example for powdery solids being pneumatically conveyed in dense phase flow with a high particle density. Due to the strong formation of dust, optical measurement methods have a lower probability to work for this application. Each powder particle forms a mass-spring system together with the air in the gaps that leads to high attenuation behavior for acoustic waves. Considering cross-sectional velocity profile inside a pipe in dense phase flow, particles of marginal layers are transported with lower velocity than particles of center layers although the velocity profile is significantly differing from the velocity profile of any Newtonian fluid. For velocity measurement methods, based on the acquisition of the Doppler shift, the risk to measure just the velocity of the outer areas of the transported mass flow increases which leads to an inaccurate estimation of the velocity and, hence, to an inaccurate value for the mass flow when the mass flow is measured by means of force measurement of mechanically decoupled sections in the transportation pipe.

Intention of the measuring system is to evaluate the transportation velocity and the velocity profile in the transportation pipe with cheap and reliable equipment by exploiting the sensitivity distribution of an electrode configuration and the rheological decomposition of a well-directed, injected perturbation.

## 2. PRINCIPLE AND THEORY

The technique of using cross-correlation is commonly used for flowmeters to measure the velocity of dense phase transported powder if an invasive measurement principle cannot be used [1]. Especially for dense phase flow of particulate solids, the formation of dunes on the upper side of the mass flow due to influence of gravity and transportation gas [2] is remarkable. These fluctuations of the homogeneity in the pipe cross-section are hardly predictable and dunes degenerate fast and spontaneously. To avoid restriction to the occurrence of these natural fluctuations and to ensure high measurement rates, artificial disturbances are brought into the mass flow periodically and well directed. These perturbations have to cause a significant difference of evaluable properties of the powder mass flow inside the pipe.

Perturbations caused by ionization of sections of the mass flow were originally considered as being a possible and precise solution for the "marking" of mass flow sections to allow later detection. Despite of using electrical field strength up to 250.000 V/m, in most measurements the effects of powder ionization due to particle-particle-friction and particle-wall-friction surpassed the effects of externally caused ionization via an electrical field. In particular, the high intrinsic ionization energy that is necessary for the breaking of strong $SiO_2$ bonds makes ionization by an electrical field ill-suited for a general purpose measurement sequence. In fact, the influence of the external field on the powder particles was just detectable using expensive precision amplifiers with an input resistance of 1 TΩ or more. For that high input resistance, the reproducibility of measurement results due to other disturbing effects was unsatisfying.

During the experiments it turned out that perturbations of the permittivity distribution and capacitance-based detection of these perturbations is best suited to fulfill the measurement task.

In most mixing processes of powdery bulk solids, the flow function is not restricted by minor injection of the mixing component in the conveyor. For the application proposed in this paper, a perturbation of the permittivity is caused by injection of water into a dry cement powder flow. The injected perturbation is displaced by the moving particles inside the pipe and the resulting permittivity fluctuation can be detected in the measurement cross-sections. Due to the fact that the pipe is not necessarily filled homogenously and that not all areas of the cross-section are transported with the same velocity, the injection of the perturbation should be done at more than one position on the pipe perimeter and affect the whole cross-section. Figure 1 shows the exemplary set-up with 4 injection nozzles and 3 measurement cross-sections. The evaluation circuitry is sketched in gray for only one pair of electrodes.

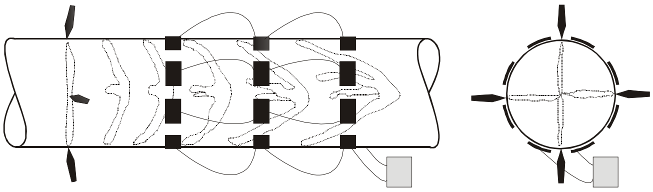

Fig. 1. Exemplary set-up of the measurement system with sketched decomposition of the perturbation

The injected perturbation and its rheological decomposition along the pipe in flow direction are also sketched in figure 1. The detectable “pattern” in the injection cross-section differs from that of each detection cross-section due to this decomposition.

## 3. CONDUCTED EXPERIMENTS

For different geometries and electrode configurations, finite element simulations have been carried out to find areas inside the pipe where perturbations of the permittivity distribution have significant effects. Figure 2 shows the field simulation for a certain geometry.

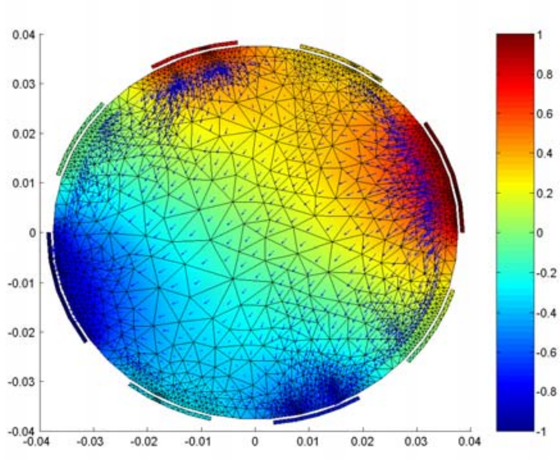

Fig. 2. Field simulation of electrode geometry with distribution of the electric potential

Sending and receiving electrodes are alternately arranged on the perimeter and sending electrodes are given a certain electric potential while receiving electrodes are floating. The distribution of the electric potential of the sending electrodes as well as their lengths have been chosen to maximize the sensitivity in the pipe center for that configuration. The colorbar on the right shows the local voltage distribution inside the pipe simulated with a grounded shield around the pipe with 15 mm distance to the electrodes while the arrows indicate field strength.

Starting from the theoretical results that were gained from the simulations, the test rig, the electrode configuration, and the evaluation circuitry were designed. The pipe that encases the transported powder is a Polypropylene pipe of 70 mm inner and 75 mm outer diameter with an relative permittivity of $\varepsilon_r = 2.4$. On the outer surface of several pieces of pipe, alternatively two and three rings of electrodes in several distances were mounted. The dimensions of the copper electrodes were advisedly chosen small for reasons of resolution and accuracy – especially in flow direction the length did not exceed a value of 7 mm. For the evaluation circuitry, the electrodes are excited with a signal with a carrier frequency of several MHz to overcome the problem of charging effects due to friction and to increase robustness with respect to external noise. All the transmitting electrodes that are excited with a signal of adjustable voltage level are connected as well as all floating receiving electrodes are. The whole electrode configuration forms an assembly of parallel-connected capacitors where the effects of simultaneous changing of relative permittivity at each pair of electrodes are summed up. This configuration has been chosen with respect to costs and the use of just one single combined control and evaluation circuit per electrode pair, independent from the number of measurement cross-sections. Depending on the relative permittivity between the electrodes, which is highly influenced by the perturbation, a certain voltage level is measurable after rectifying. This data acquisition was performed with a PCI-9118DG A/D converter card in LabView using a sample frequency of 7 kHz.

To get reliable and reproducible results in the test phase of the measurement system, plastic plugs of distinct shape were used instead of transporting amorphous solids whose behavior is by far more difficult to predict and to simulate. Plastic plugs were tested in free fall experiments and inclined fall experiments. Due to the relative permittivity of the test plug and the perturbation changes the electric flux lines are bent in direction of the arriving test plug before reaching the measurement cross-section. For this reason, less capacitance and thus a lower voltage level is acquired a short time before a changing of permittivity gets active in the measurement cross-section. With the entrance of the test body into the sensing field of the electrode configuration, the voltage raises about 700 mV and forms a plateau for the time when the plug is in the field. A decline of again 700 mV is measured when the plug passes the configuration.

Representative for a plastic plug, figure 3 shows a test body of 150 mm length and 65 mm diameter where two 4 mm holes were drilled up to the half of the plug’s diameter. Both holes with a volume of 400 $\text{mm}^3$ are perturbations of the otherwise homogenous permittivity distribution.

Fig. 3. Test plug for fall experiments with perturbation

To ensure comparable conditions for the plug experiments and a later practical use, the two disturbances in terms of holes were filled with dry cement powder in a way it will appear in the practical application in dense phase transportation. The influence of cement powder in the holes is acquired by conducting inclined fall experiments of the disturbed plug through the pipe. Figure 4 shows this plateau, acquired for the duration when the test plug is in the sensing field of a pair of electrodes, and the typical effect of an undisturbed plug fall experiment and a cement-powder disturbed experiment.

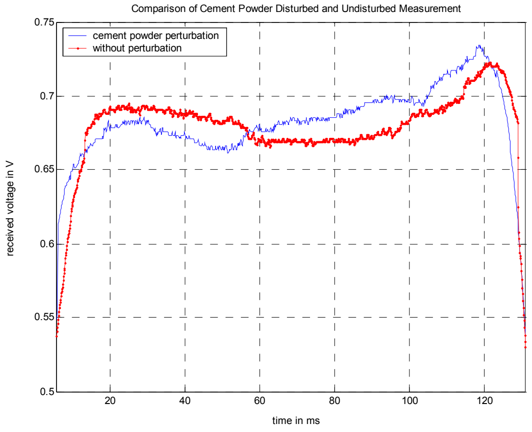

Fig. 4. Signal-comparison of cement powder disturbed and undisturbed plug fall experiment

In several conducted experiments, the deviation of the acquired voltage level at the electrodes confirmed that the relative permittivity of the test plug equals the relative permittivity of dense phase conveyed cement powder sufficiently accurate.

Furthermore various perturbations of the mass flow have been simulated in terms of bringing changes of the relative permittivity onto the test plug as well as simulating the effects of these changes in a finite element model. All of the measurements carried out show a “frozen pattern” disturbance [3] like it is presented in figure 5 and 6. For these figures, the first hole in flow direction of the test plug in figure 3 was filled with water ($\varepsilon_r \approx 80$) and the second hole included air ($\varepsilon_r = 1$). In the plot in figure 5 both, the signal of the disturbed and the undisturbed test plug at one pair of electrodes, is given. Other pairs of electrodes on the pipe perimeter that are less affected by the perturbation show a smoother signal behavior, which enables a localization of the perturbation. The plot in figure 6 shows the resulting signal when the undisturbed measurement result is subtracted from the disturbed one to isolate the influence of the perturbation graphically. Significant peaks of about + 130 mV for the water disturbance and – 40 mV for the air disturbance are visible in the plots.

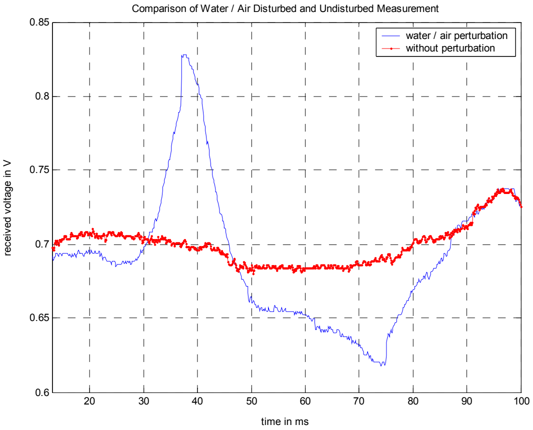

Fig. 5. Signal-comparison of water and air disturbed and undisturbed plug fall experiment

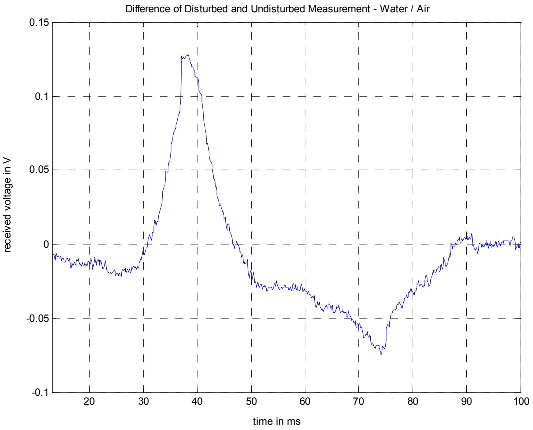

Fig. 6. Difference plot of water and air disturbed and undisturbed plug fall experiment

It has to be mentioned that although air perturbations are possible, water injections are preferred because of higher impact of the perturbation and because of agglomerating effects with the powder that is more and more alike a more calculable “frozen pattern” decomposition. For different velocities and accelerations, data series have been acquired to compare measurements and FEM simulations.

Due to the parallel-connected configuration chosen, only one injected perturbation may occur inside the pipe between the first and the last measurement cross-section. The number of injections per second depends on the required number of measurements per second.

When design and dimensioning of circuitry and electrode configuration have been completed, several inclined fall experiments with (disturbed) cement powder were carried out with special emphasis on reproducibility and assignability of the insights derived from test plug experiments. Water perturbations were injected manually to test effects of penetration depth and deformation of the perturbation. Here as well the reliability of the FEM simulation results could be verified and resolutions of perturbation detection of less than 10 mm could be achieved at velocities of several meters per second.

Shielding and robustness against external field effects are essential for a capacitive application working with such small capacitance changes. Unshielded, any external field influences the measurements with the electrode configuration in a way that field strength arrows are deflected due to the external field instead of ending at the receiving electrode. A grounded shielding assures insensitivity towards external field influences. Simulations as well as experiments showed a good performance when the shield is mounted co-axially to the sensing electrode rings in a distance of about 15 mm.

Main target of the testing and dimensioning phase for the measurement system was to make the electrode configuration as sensitive as possible to well-directed inserted perturbations to reduce the amount of injected water to a level that can be inserted by injection nozzles that are commonly used in automotive engineering.

## 4. VELOCITY AND VELOCITY PROFILE

Along the tube in flow direction, the perturbation is subjected to rheological decomposition as shown in figure 1. With a certain delay and a certain deformation, the injected perturbation reaches the first of the measurement electrodes where it causes a deviant reading due to the deviant value of the relative permittivity of the perturbation between the electrodes. When the displaced perturbation moves into the sensitive area of the other measurement electrodes, both, the delay between injection and occurrence at the electrodes and the deformation of the perturbation increase. The delay of the significantly differing signals between according pairs of measurement electrodes is directly related to the transportation velocity – the degree of deformation is evaluated for the velocity profile of the mass flow inside the pipe.

The sensitivity of the electrode arrangement concerning effects of alterations of the relative permittivity is shown in figure 7. Areas of higher sensitivity are shown in a brighter color in this sensitivity map.

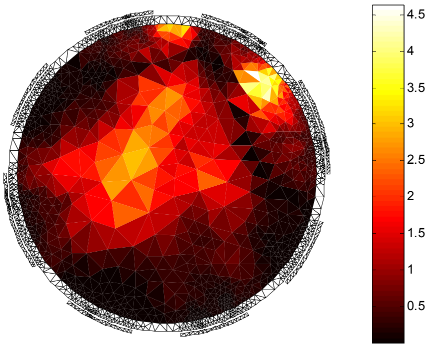

Fig. 7. (a) Sensitivity map for electrode 2

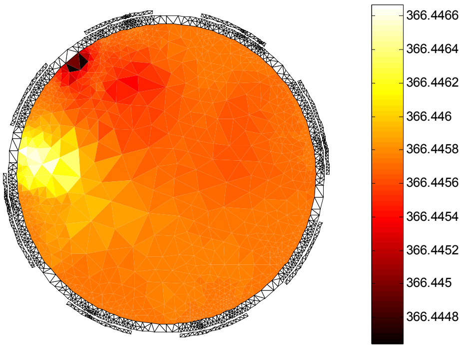

Fig. 7. (b) Sensitivity map for electrode 4

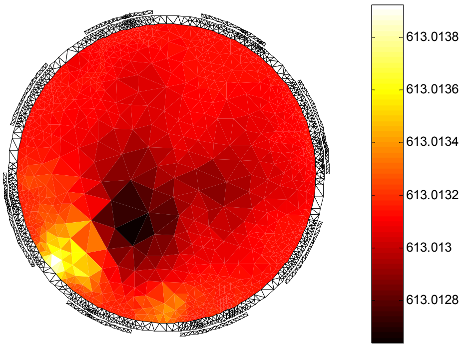

Fig. 7. (c) Sensitivity map for electrode 6

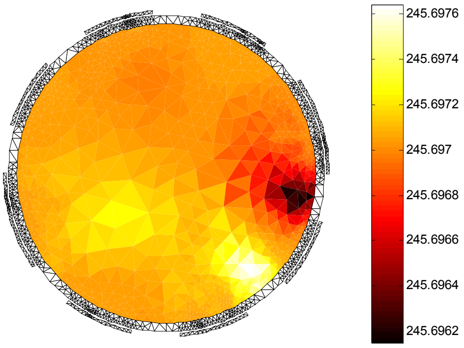

Fig. 7. (d) Sensitivity map for electrode 8

Fig. 7. Sensitivity distribution of the electrode configuration

Delayed by a certain time, the effects of the perturbation in each measurement cross-section are received in each pair of electrodes and, in consequence of the parallel-connected configuration, summed up in the evaluation circuit.

When the first disturbed particles of the flow reach the first measurement section, the value of each capacitance and thus the measured values of the voltage level at the output of each evaluation circuit start to increase. As a result of the perturbation’s deformation and the sensitivity distribution of the electrode configuration, center regions of the cross-section will be affected first which leads to a small increase of the output voltage according to the sensitivity distribution in figure 7. When regions with lower velocities, which are closer to the border of the tube, reach the sensing field of the measurement electrodes, the readout of the evaluation circuits increase sharper. The bypassing of the perturbation is indicated by a sharp decline of the output voltages.

Level detection and the building of the signal center point to measure the time difference between two perturbation detections is assumed to be imprecise and thus the signal is auto-correlated according to

$$\Phi_{11}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{0}^{T} x_1(t).x_1(t-\tau)dt$$

where $\Phi_{11}$ has its maximum when $\tau$ is the time difference between two perturbation effects at different pairs of electrodes, which are matching best for that certain $\tau$ value. By using 3 measurement cross-sections, the decomposition of the perturbation can be observed over a larger section and an auto-correlation function is executed twice.

Further research is done to develop a preferably precise model of the rheological decomposition of the displaced perturbation, including agglomeration and friction as well as pressure and velocity influences inside a tube in dense phase transportation to enhance the velocity profile acquisition.

With the knowledge of the transportation velocity and an accurate velocity profile it is possible to measure the mass flow by means of force measurement of mechanically decoupled sections in the transportation pipe.

## 5. OUTLOOK

For further work, the injection of the perturbation is planned to be done by injection nozzles that are electrically controlled and that insert a short, focused beam of water into the mass flow of powdery solids.

As shown in figure 1, electrically controllable injectors are planned to be mounted on the exterior of the pipe as well as 3 measurement cross-sections each consisting of 4 pairs of electrodes. A small amount of water is injected by the nozzles up to the half of the pipe-diameter. With the knowledge of the spaciotemporal rheological decomposition of a perturbation at dense phase conveying, the correlation function can be improved in a way that the perturbation and thus the signals can be predicted to enlarge the inner coherence for correlation. The procedures are sketched in figure 8. For (d) the dotted line indicates that the signal (a) can be matched either to the positive or to the negative slope of the signal (b), leading to similar peaks in the correlation function. Fitting the predicted signal (c) to (b) instead, leads to a more precise matching (compare (e)).

Depending on accuracy requirements and the degree of rheological decomposition of the perturbation in the pipe, the duration of injection should be as short as possible to achieve a compact and localized change of the permittivity distribution in flow direction.

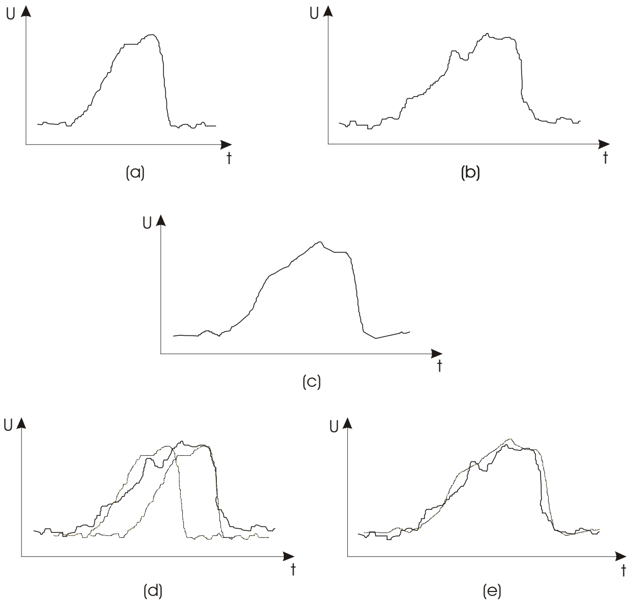

Fig. 8. Measured signals (a) and (b), the predicted signal (c), and the matching of those signals (d) and (e).

## 6. CONCLUSION

Transportation velocity and the velocity profile are necessary measurands for the mass flow measurement. The presented method for measuring velocity as well as the velocity profile of dry powdery solids inside a pipe is based on periodical injection of perturbations and the auto-correlation based evaluation of time differences as well as the influence of the rheological decomposition of the perturbation. The acquisition of the voltage level of the output circuitry at each pair of electrodes yield the transportation velocity and the velocity profile over the pipe cross-section. As a future work, the exploration of the rheological interrelationship for dense phase transported amorphous solids will be deepened to ensure a reliable measurement equipment for the velocity profile.

## REFERENCES

[1] A. Arko, R. Waterfall, M. Beck, T. Dyakowski, P. Sutcliffe, M. Byars, "Development of Electrical Capacitance Tomography for Solids Mass Flow Measurement and Control of Pneumatic Conveying Systems", *1$^{st}$ World Congress on Industrial Tomography, Buxton,* April 14-17, 1999.

[2] G. Pajer, F. Kurth, "Fördertechnik Stetigförderer", p. 299

[3] M.S. Beck, A. Plaskowski, "Cross Correlation Flowmeters – their design and application", pp. 36-38

**Author:** Dipl.-Ing. Anton Fuchs,
Institute of Electrical Measurement and Measurement Signal Processing, Graz University of Technology, Austria
Kopernikusgasse 24/IV, A-8010 Graz, Austria
Tel: +43 (0)316 873 7274
Fax: +43 (0)316 873 7266
Email: fuchs@emt.tugraz.at