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Capacitive sensor and its calibration- A technique for the estimation of solid particles flow concentration

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Abstract. The precise and accurate measurement of flow rate in the batch flow of the solid particles is of primary importance in many process industries for the improvement of the efficiency of the system. Many techniques developed for the measurement of mass flow rate. The capacitive sensors has a significance of being non-invasive, higher accuracy and low cost for mass flow measurement despite the fact that many factors adversely affect the performance- including non-uniform flow, multiphase flow, temperature, pressure, and moisture in the solid particles. This paper covers preliminary investigations of the offline estimation of mass flow concentration based upon the calibration of capacitance electrodes to quantify the mass of dielectric as a function of capacitance variation between the electrodes.

1. Introduction

The batch flow of solid particles finds its application in many process industries including food, chemical and thermal [1]. In many industrial applications, solid particles like coal in furnace system or minerals in the mining industry transferred by a pneumatic force [2,3]. In order to improvise the quality of the product and the efficiency of the manufacturing process, there is always a need for the online monitoring, data logging and control of the pneumatic conveying operations- the precise and accurate measurement of the flow parameters among which mass flow rate, flow pattern and mass of solid are of primary significance[4,5]. Depending upon the sensing techniques, different advanced and sensitive flow rate measurement methods for solid particles have been developed and investigated. Methods like digital imaging, optical sensing, acoustic techniques, radiometric methods, electrostatic sensors, and capacitive sensors used for the measurement of Gas/Solid particles flow rate measurement [6,7]. The processes like acoustic technique, optical sensors, and digital imaging work well when the concentration of solid particles is dilute. The radiometric method used regardless of the concentration of solid particles despite the fact that there is a chance of radiation leakage that can be avoided by proper shielding. The urge for low cost, more reliable, safe and rigid sensor for the solid

particles flow rate measurement without any invasive alteration in the channel developed electrostatic and capacitive sensors. Capacitance measurement technique is widely used in both online and offline estimation of these parameters because of its low cost, better accuracy, fast response, and its non-invasive measurement techniques [8]. Despite the fact of being simple, robust and dynamic in its response, several factors try to adversely affect the system response thus inculcating errors- the multiphase complex and variable flow, non-uniform sensitivity distribution of the electrode pair, the deposition of the solid particles on the internal walls of the channel's area where the electrodes are attached- moisture, solid composition, particles size, and contents [9].
This paper covers the preliminary investigations of the off-line estimation of the mass flow concentration of solid particles in a channel using the capacitive method. The main idea revolves around the calibration of capacitive electrodes that will quantify the mass of the solid particles as the dielectric is flowing between the electrodes through the channel. The flow of the sand particles is based upon the assumption that the particles are moving parallel to the axis of the pipe and perpendicular to the plane of the sensor such that every passing particle has to flow through the sensor.

2. Theoretical Background

The dielectric material, the distance between the plates and the area of each plate defines capacitance value [10]. The capacitance is expressed in terms of its geometry and dielectric constant as equation (1)

$$C = \varepsilon_r \frac{\varepsilon_0 A}{D} \quad (1)$$

Where C is capacitance in farads (F); ε_0 is the permittivity of free space (8.854x10-12F/m); ε_r is dielectric constant/ relative static permittivity of the material between the plates; A is area of each plate (m^2); D is separation between the two plate (m). Keeping other parameters of dimensions of electrodes and distance between the electrodes constant, the variation of the quantity of dielectric in between the electrodes changes the capacitance value in a direct relation [11,12,13]. Knowing the relationship between the capacitance and mass of solid particles, the variation of capacitance as a function of time represents the mass flow rate of the solid particles sliding between the electrodes. If C_0 is the capacitance of empty sensor, the capacitance can be stated in terms of the dielectric constant as shown in equation (2) [14].

$$\mathrm{C} = \varepsilon_{\mathrm{r}} \mathrm{C}_0 \quad (2)$$

2.1Mass Flow Rate

The mass flow rate of pneumatically conveyed solids can be denoted by equation (3)

$$M(t) = \rho_s A V_s(t) \beta_s(t) \quad (3)$$

Where ρ_s is the density of the solids; A is the effective cross section area of the pipe; $V_s(t)$ is the particle velocity and $\beta_s(t)$ is the volumetric concentration of the solids. In solid particles, different materials exhibit different flow behaviour. In addition, several factors affect the mass flow rate of the solid particles. Moisture content in the solid particles produces cohesive strength. The cohesiveness is also visible by temperature variation. Few solids are sensitive to rise in temperature. Others are reactant to a constant temperature. Cohesiveness is also dependent upon particle size. Finer powders are more cohesive also they have higher wall friction and thus difficult to flow smoothly [15]. If the solid particles are allowed to stay at rest for a longer time, the compaction loads due to head pressure can produce a strong cohesive bond. A chemical reaction, crystallization, or adhesive bonding can also cause this. Sometimes, after a cohesive arch is broken up, say by somehow initiating flow, the material can revert to its original flow condition and not exhibit a similar cohesion if left at rest again. On the other hand, some materials will time and again, bridge and rat-hole even after flow is re-initiated [16].
A method to find the mass flow concentration is based upon the calibration of the electrodes. In this method the cubic volume of the channel covered by a pair of electrodes such that both are parallel to each other -one at the upper and the other at the lower flat surface of the channel covering top and the bottom surface completely to ensure that all the flowing solid particles will pass between these

electrodes is closed and a known mass of the solid particles is fed to this volume. The change in capacitance is observed. Moreover, the process is repeated for several values of mass. Changing the quantity of the solid particles, the graph plotted between the quantity of dielectric-mass of solid particles and the change in capacitance [17]. The assumptions for this case held that all the mass fed for testing is accumulated between the electrodes. In addition, the effective area of capacitive lines of force is just between the parallel plates while the effect in fringe lines of force is ignored [18,19].

3. Experimental

The capacitive sensor assembly system consists of three main components: the sensor, the data acquisition circuit, and a computer. The sensor is a single or more pair of metallic electrodes. The size, shape and the distance among the electrodes of an individual pair are adjustable as per requirements. These electrodes are mounted on the insulated pipe, which is extraneously covered with the earthed metallic sheet. The data acquisition circuit: typically excite the capacitive electrode pair and converts the capacitance into the voltage, which are conditioned and digitized for data acquisition. The computer store and analyse the data by applying different mathematical techniques [20].

The block diagram of the experimental setup is shown in fig.1. It consists of a feeder with a motor of variable speed to change the frequency of vibration of the base of the feeder to adjust the speed of flow of solid particles. These particles flow through a rectangular, insulated and inclined channel-fixed on a stand and the angle of inclination can be varied as per requirements. The dimensions of the channel are 1x2x60 cm^3. A pair of electrodes ‘Sensor A’ of dimensions 2x1 cm^2 is fixed on the lower and upper surface of the channel such that all the solid particles flowing through the channel must flow through ‘Sensor A’. The volumetric region enclosed by the sensor is 4cm^3.The channel is enclosed in a metallic shielding attached to a common ground with protective metallic shielding attached at the upper and lower ends of the sensor to minimize the effects of the noise signals.

Eval AD7746EBZ is a capacitance to digital converter that is primarily used as data acquisition circuit for the measurement of capacitance between the electrodes. The main significance of AD7746 is its high resolution of 24-bits down up to 4aF and accuracy up to 4fF. Its full-scale capacitance rage is ±4pF. The maximum sampling rate of the device is 90Hz. The capacitance to be measured is directly connected to its terminals- Excitation terminal and Input terminal. It communicates through the I2C interface with a microcontroller- Arduino UNO.

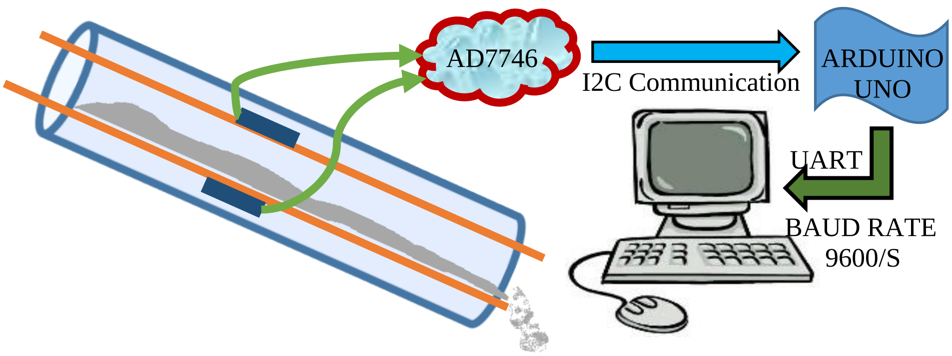

Fig. 1. Block diagram of the system.

The registers are configured according to the Data Sheet for single mode capacitance measurement using I2C communication protocol. The raw data from AD7746 is received by Arduino and sent to Computer through UART where the values are fed in the formula to compute the capacitance. The computer programme also gives the desired sampling interval to the Microcontroller that starts dropping the data and thus stores at the required sampling rate [20]. The flow diagram of the data acquisition and storage is shown in fig. 2.

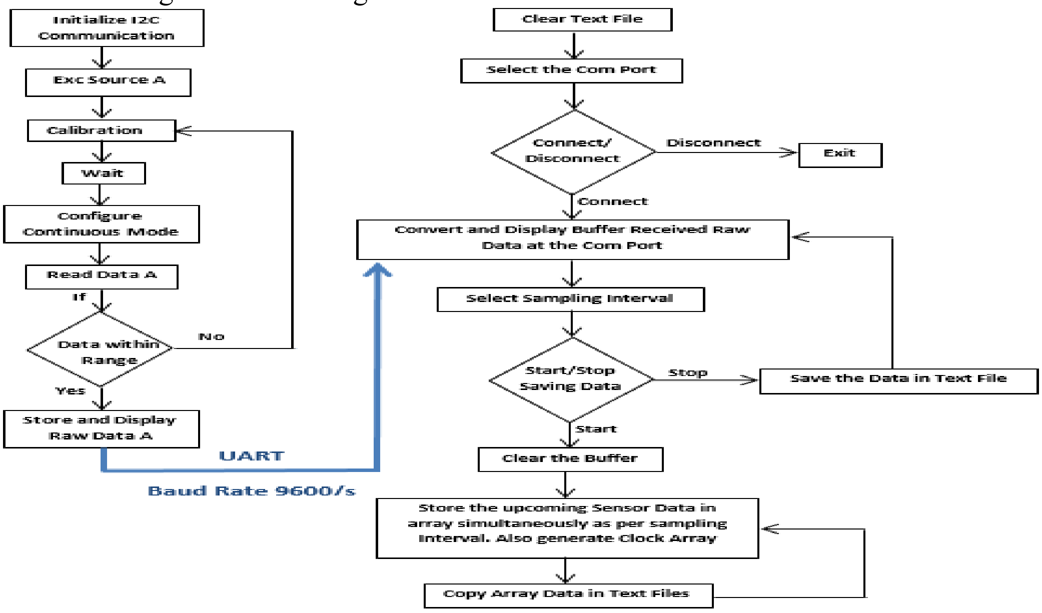

Fig. 2: Flow Diagram for Data Acquisition and Data Storage

4. Results and Discussion

Table 1 shows the relationship between the mass of the sand- dielectric and the capacitance produced. The values are observed in calibration where the known mass of sand is placed between the plates ensuring that sand is in between the electrodes. The capacitance variation is non-linear with the change in dielectric mass and gradually capacitance becomes constant. The relationship between the mass of sand (w) and capacitance value (C) is found from curve fitting tool using Matlab R2018a and is given by equation (4).

$$C(w) = 0.000163w^3 - 0.009325w^2 + 0.171w + 0.4729 \quad (4)$$

Table 1: Mass of Dielectric and Average Capacitance in the Sensor Electrodes

Mass (g)	0	3	5	8	10	14	16	19	24	28	35
Capacitance. (pF)	0.495	0.796	1.2006	1.381	1.4019	1.4473	1.4535	1.4948	1.5036	1.5158	1.514

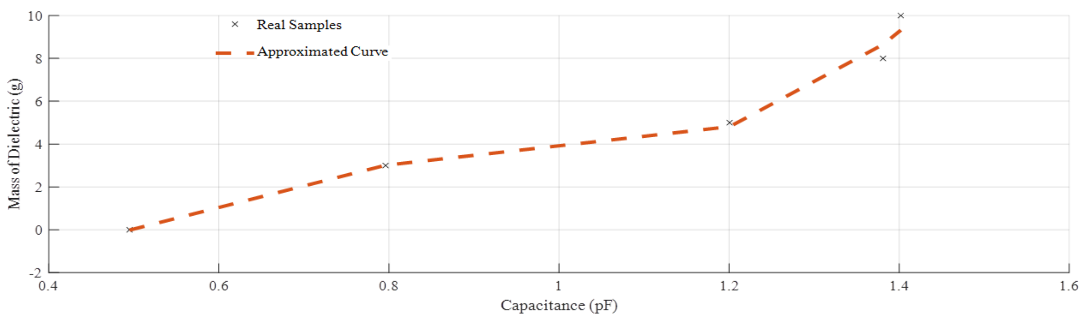

Fig. 3. Quantification of Dielectric from Capacitance**.**

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The mass of sand-dielectric as a function of capacitance can also be found from the curve fitting technique to quantify the amount of sand between the electrode plates from the capacitance value. From the data of capacitance variation caused by dielectric mass flow, the value of the capacitance never exceeds 0.55pF. For simplicity of approximation, interpolant approach is used where

$$\mathrm{w(c) = A(c) + B(c)} \tag{5}$$

Here $A(c) = w(c)$ when capacitance varies from 0.4950pF -1.4pF. From the data of table 1; using curve fitting tool, adjusting the range of capacitance variation from 0.4950pF-1.4 pF; the relationship of the mass of sand as a function of capacitance is given by equation (6) and is shown in fig. 3

$$W(c) = 41.4c^3 - 111.1c^2 + 100.8c - 27.71 \tag{6}$$

Fig. 4 shows the capacitance values and the corresponding mass of dielectric values calculated from equation 6 during a flow of total 364g of sand for a period of 18.26 seconds. The values thus obtained are instantaneous values of mass flow. Their sum is equal to 330g, which is in accordance with the actual mass flow during this interval.

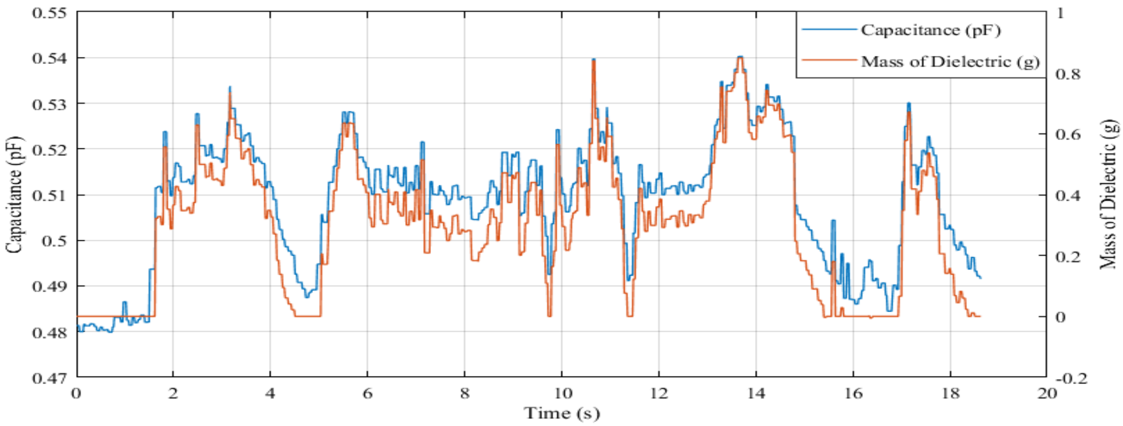

Fig. 4. Capacitance (pF) and Equivalent Mass (g) Values during Flow of Dielectric through the Channel

The mass flow concentration was calculated by dividing the mass of dielectric by the volume occupied by the sensor.

Table 2: Comparison of Actual and Estimated Average Mass Flow Concentration

Sr. No	Time (s)	Actual Cumulative Mass (g)	Estimated Cumulative Mass (g)	Error	FC_{MAX} (g/cm^3)	FC_{AVG} (g/cm^3)	FC MEDIAN (g/cm^3)
1	18.26	364	330	10.30%	0.212	0.0754	0.0805
2	24.44	493	470.85	4.70%	0.2233	0.0818	0.0821
3	68.93	1000	910.85	9.79%	0.1634	0.0561	0.0529
4	19.39	232	205.36	12.97%	0.1504	0.0450	0.0345
5	42.51	500	482.24	3.68%	0.1334	0.0482	0.0406

Table 2 shows the percentage error in estimating the total mass flow using capacitive sensor. It is essential to mention that the flow was not constant and kept fluctuating. The max flow concentration (FCMAX) average flow concentration (FCAVG) and median flow concentration (FC MEDIAN) – an instantaneous value at the center of the whole process of calculation were calculated for different iterations.

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5. Conclusion and Future Work

This paper reports an experimental study of solids flow in pipes using capacitance measurement. A procedure is derived for the calibration of capacitance to quantify the mass of dielectric flowing through the capacitance electrodes as a function of the variation of the capacitance value. The results so obtained are quite close to the calculated results from the weighing scale as shown in table 2. However, it is ensured that solid particles must be dry and the flow of all the solid particles should be between the two electrode plates also the velocity of the solid particles should be of moderate value. This work can be further extended to a calculation of the velocity of solid particles and the effect of the inclination angle of the channel on the velocity of the solid particles. Calibration can also be used to quantify the moisture content in a known mass of solid particles and the effect of moisture on the flow of the solid particles. Future studies may aim to improve the structure of the electrode arrangement, so that the measurement can adapt to more flow patterns produce more accurate results.

6. Reference

[1] Dias T, Melchert W, Kamogawa M, Rocha F, and Zagatto E 2018 *Talanta*,**184** 325

[2] Wei Z J, Du C long, and Ma Z Ling 2018 *Powder Technol*ogy **339** 470

[3] Lu H, Guo X, Li P, Liu K, and Gong X 2017 *Chem. Eng. Res. Des*, **120** 208.

[4] Seraj H, Rahmat M F, and Khalid M 2013 *Sci. Iran.* **20** 786

[5] Rao S M, Zhu K, Wang C H, and Sundaresan S 2001 *Ind. Eng. Chem.* Res. **40** 4216

[6] Hartmann C, Wang J, Opristescu D, and Volk W 2018 *Opt. Lasers Eng.* **107** 127

[7] Lima M B, Andrade S I E, Barreto S,Almeida L F, and Araújo M C U 2013 *Microchem. J.* **106** 238

[8] Zhang W, Wang C, Yang W, and Wang C H 2014 *Adv. Powder Technol.* **25** 174

[9] Che H Q, Wu M, Ye J M, Yang W Q, and Wang H G 2018 *Flow Meas. Instrum.* **62** 223

[10] Mohamad E J, Rahim R A, Rahman M H L, American H L M , Muji S Z M, and Marwah O M F 2016 *Flow Meas. Instrum.* **47** 62

[11] Kondrat S, Kornyshev A, Stoeckli F, and Centeno T A 2013 *Electrochem. commun.* **34** 348

[12] Rao G and Krishnamurthy C V 2017 *J. Electrostat.* **87** 19

[13] Yang M X and Yang F 2017 *J. Electrostat.* **87** 276

[14] Terzic E, Terzic J, Nagarajah R, and Alamgir M 2012 *A Neural Netw. Approach to Fluid Quant. Meas. Dyn. Environ.* **9781447140603** 1–138

[15] Chen W and Roberts A W 2018 *Powder Technol.* **325** 639

[16] Lu H, Guo X, Jin Y, and Gong X 2018 *Chem. Eng. Res. Des.* **133** 326

[17] Zhang L, Zhai Y, Wang X, and Tian P 2017 *Measurement* **126** 223

[18] Li X, Jaworski A J, and Mao X 2018 *Flow Meas. Instrum.* **62** 255

[19] Sun M, Liu S, Lei J, and Li Z 2013 *Meas. Sci.* **19** 67

[20] Huang Z, Zhu J, and Lu L 2011 *Key Eng. Mater.* **483** 461

IOP Conf. Series: Journal of Physics: Conf. Series **1311** (2019) 012046 doi:10.1088/1742-6596/1311/1/012046

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