Experimental evaluation of agricultural biomass flow sensing behaviour using capacitive technique

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Abstract. To enhance industry control quality level as well as uphold enterprise economic benefit precise sensing and measurement of biomass flow is a major concern among researchers worldwide. Keeping in mind the shortcomings of existing sensing technologies this paper has developed a capacitive sensing method by making use of aop amp based bridge circuit along with particularly designed sensing electrodes. The objective of this work is fulfilled via experimental validation through a prototype hardware implementation of a flow sensing set up. The experimental results have specified the measurement system which is able to sense flow variation as a change of dielectric permittivity of different biomass materials under room condition. Moreover, the obtained results have revealed distinctive features clearly signifying the shapes and physical characteristics of electrodes, locations of the mounted electrodes on test pipe wall, dielectric permittivity and characteristics of test biomass materials.

1. Introduction
Processes relating biomass materials are of emergent concern, although handling and conveying biomass particles are quite challenging and complex because of its unusual physical properties. Over the recent past years, researchers have been researching and reporting works on using various techniques for biomass or gas-solid flow measurement. The wide-spreading applications of agricultural biomass (e.g., grains, flour, and corn) are found not only in the food processing industries but also in chemical, pharmaceutical industries and power plants. A comprehensive overview has been conducted by some researchers on agricultural biomass particles flow measurement techniques [1]. When biomass particles are subjected to multiphase flow, it faces distinctive challenges since these are particularly anisotropic. Also atypical features like large mean particle sizes, extreme shape including flakes, chips, fibres, wide size distributions, general heterogeneity of biomass particles make the sensing and mass flow measurement challenging. Among all the sensing techniques, capacitive technique has proven to be much more reliable than the other techniques in term of sensitivity and cost namely electrostatic, optical, ultrasonic, microwave etc. In capacitive technique, the measured capacitance can be used to visualize the phases’ concentration ratios [2]. In [3] the researchers developed a computer processing system including a measurement model unit for measuring agricultural powder flow rate based on the

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measurement values of the total pressure drop of gas-solid two-phase flow and the concentration of powder. Differential pressure transducer, a capacitance concentration sensor, a pressure transducer, and a temperature transducer were used in this technique. Some researchers developed capacitive sensing techniques implying novel measurement circuits with innovative electrode shapes. For past few years this technique has been being used vastly in industrial sectors in order to monitor the flow of dry agricultural powders [2].

Moreover, a number of capacitance measurement techniques were developed earlier and further implemented in Integrated Circuit (IC) which have been reported [5-6] to make the conversion of capacitance-to-digital (CDC). An innovative capacitive sensor [7] with ring and concave type electrode has been proposed for void fraction measurement and flow pattern identification. In [8] the authors developed a multi-electrode sensing structure (11 ring shaped) for enhancing the sensitivity to dielectric permittivity variations. In [9] the authors conducted a brief overview on the developed capacitive measurement techniques over recent years for the application of flow measurement in process instrumentation. Also a capacitance based sensor to measure industrial process parameters and a capacitance-to-digital conversion system were developed in this paper. Such technologically advanced multi-purpose capacitance-to-digital conversion hardware can work under several carrier frequencies. In order to validate the real-time utility of flow sensor, different electrode geometries with the application of potential electrode excitation modes are implied by some authors in [10]. Here, the sensor electronic is comprised of a capacitance to digital converter Application Specific Integrated Circuit (ASIC) and a Digital Signal Processor (DSP) running on C. Linux Operating System. A good level of sensitivity is not maintained due to material changes inside the measuring volume that contributes to measurement inaccuracies. Most of the existing technologies made use of complex measurement interface circuit model as well as electrode arrangement used for flow piping arrangement where the effect of stray capacitance is a key issue. On top of this, it is more challenging while focusing at the types of electrodes, unusual particle size of biomass, and the accuracy and simplicity of the measurement electronics circuit.

In this paper, the developed sensing system can detect very slight capacitance variations through reducing stray and residual capacitance effect. Two agricultural biomass materials or grains namely: fodder (cattle food) and flour are used as biomass test materials under similar flow and measurement condition in normal room temperature. This paper is organized as follows: Section 2 introduces the methodological foundation of the sensing system architecture along with measurement interface circuit. Experimental approach along with results is presented in Section 3. Section 4 details discussion and finally the paper is concluded in section 5.

2. Sensing System and Measurement Interface
The Capacitive sensing technique for biomass flow works on the basic principle of particulate flow within a capacitive sensing volume through causing changes in the dielectric constant of gas/solids mixtures. Flow sensing system comprises of a custom developed horizontally and vertically connected pipe on which capacitive sensing electrodes are fitted. Five pairs of sensing electrodes are hereby connected on the pipe section with a measurement interface circuit which is based on an adjusted bridge network. The block diagram of sensing system is presented below in Fig 1.
The signals obtained at the end of the measurement interface circuit become a source of information for flow sensing of agricultural biomass materials. Figure 2 illustrates the measurement interface circuit.

![Measurement Interface Circuit](image)

The measurement interface circuit is built with operational amplifiers. The lower bridge arms’ pair is built of resistors where point B remains at virtual ground for better stability of flow sensing by the variable capacitance arm Cx. It diminishes the stray capacitance effect in between the output leads of bridge network. The bridge output will be in voltage form being linearly balanced with capacitance change for different biomass concentration during flow phenomenon. The output voltage derived from measurement interface circuit is,

\[
V_o = -j\omega V_{R_1} R_{R_1} \frac{C_x - C_0}{R_3 R_2}
\]  

(1)

The review indicated that the identified criteria were not being met with existing products and highlighted the techniques of sensing and transmission of information as major areas requiring attention in the development of a system.
3. Experimental Detail and Result Analysis

The sensing set up uses an industrial vacuum pump for sucking the fodder and flour materials independently by means of a horizontal and vertically linked polyvinyl chloride 1000 mm pipe with an inside diameter of 25 mm and outside diameter of 27 mm. The following Figure shows the images of test materials used to conduct the experiments. In the test section, five capacitance sensors for the measurement of capacitance are located keeping certain distances through a 1000 mm horizontally and vertically connected pipe. Two pairs of electrodes are mounted which are constructed by mild steel and circular electrode and another three pair are made by semicircular plates. Moreover, the ratio of electrode width W to electrode separation d is made 4:1, the total number of electrodes are K = 10, the electrodes’ width are W =12 mm, electrode separation d = 3 mm (As in Figure 2)

![Electrode structure](image)

The schematic of custom developed electrode shapes are given in the following Figure.

![Fig. 4 Schematic of electrode shapes](image)

The calibration is made for bridge circuit to balance the bridge for no flow. During unbalanced condition of bridge biomass flow gets started in flow piping system which is depicted in Figure 4. The flow piping system involves a stunner at the extreme end for making the materials flow through the pipe whereas an industrial suction motor for sucking the materials which get stored in collector bag at the other end.
Firstly fodder and flour biomass materials are flown at 1000g/min and at 600g/min respectively. The measurements of capacitance changes (in Pico-farad) and voltage outputs (in Volts) are kept in record in every 10 seconds of flow and shown in the following bar graphs. Figure 6 a-e) shows the voltage outputs and capacitance bar graphs. The semicircular electrode SC (mounted close to the container and on vertically upward pipe section) achieved the maximum output voltage with maximum capacitance due to location reason. The SB electrode (horizontally placed) demonstrates the minimum capacitances (65.6-68pF) throughout the whole flow period. Semicircular SA (close to the suction pump and on the vertically downward pipe) illustrates fluctuated and varying voltages while the capacitance sensed showed no obvious fluctuation. The similarity in such pattern shows the effect of identical location on test pipe wall.
Fig. 6 Bar graph of fodder flow (1000gm/min) for (a) circular CA (b) circular CB (c) semicircular SA (d) semicircular SB (e) semicircular SC
Even though possessing dissimilar physical properties of electrodes, both SB and CB have shown matching behavior in the measured voltages. As a continuation, the other biomass material flour is flown and once again the bar graphs in Figure 7(a)-(e) have pointed up proportional correspondence between the capacitance sensed and output voltage obtained for different electrodes confirming the proper functionality of measurement circuit.

![Bar graph of flour flow (600gm/min) for (a) circular CA (b) circular CB (c) semicircular SA (d) semicircular SB (e) semicircular SC](image)

**Fig. 7:** Bar graph of flour flow (600gm/min) for (a) circular CA (b) circular CB (c) semicircular SA (d) semicircular SB (e) semicircular SC
The bar graphs proved that the voltage and capacitance graphs showed consistent results when looking at the electrodes’ location (same as previous sensing behaviour), types and physical properties. Like fodder the dissimilarity of flour materials has been sensed well by circular electrodes when semicircular ones showed steady response mostly. Because of having bigger diameter (500μm) of fodder, it flows faster than the fine particle Flour (shaped as 100μm). The dielectric permittivity has also proven its effect on the sensed results. Fodder materials having dielectric permittivity of 2.5-3.0 has shown its effect on the capacitance and voltage waveforms which are higher and smooth in comparison with these of flour. Due to the variation in the flow regime in the measurement pipe, the capacitance has been increased and decreased accordingly which has shown its effect on the voltage output. Eventually the final output has been recorded with different biomass flow rate in the flow pipe. In the present scheme, very small capacitance variation has been converted into voltage variation by using a simple low cost operational amplifier based capacitance bridge circuit. The recorded values sensed by the electrodes across the sensors are directly related to the air-biomass phase distribution, shape and physical characteristics of electrodes, locations of the mounted electrodes on test pipe wall and physical characteristic as well as dielectric permittivity of test biomass materials.

4. Discussion
Due to the atypical characteristics of biomass materials, industrial biomass processes have not shown expected outputs in terms of measurement interface circuit used in capacitive sensing techniques. Hence, the prospective of biomass as a means of highly regulated generation of renewable energy source is yet to be perceived fully. This paper has looked into a rare research issue to let the unrealized biomass resources recognized. The positioning of the electrodes has shown noteworthy effect on the measured data. The nearest electrodes from the biomass container have shown larger concentration (both in terms of capacitance and voltage sensed) than the other parts. Moreover as the galvanized iron semi-circular electrodes have better conductivity than that of mild steel circular ones, sensitivity have been shown to be relatively better for semicircular ones. On the whole, the multiphase flow sensing as well as flow sensing of biomass process instrumentation is addressed in this paper through realizing the sensing behaviour of two different agricultural biomass materials’ flow; particularly concentrating at the types and design of electrodes, the irregular particle size and the efficiency of measurement electronics.

5. Conclusion
In this paper, the experimental work has been carried out in line with the aspect stated in the research problem, tuning the findings to achieving the research objectives. The developed system is able to detect very minor capacitance variations offsetting stray and residual capacitances’ effect. This sensing system has been validated to be used in real time flow measurement by setting up a data processing unit in a Programmable Logic Controller (PLC)-based environment for measuring mass flow rate as well as concentration and velocity of biomass materials. The useful data extracted from real time flow measurement will allow the plant operators enhancing flow control of process instrumentation.

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