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Electrical capacitance as a proxy measurement of miscanthus bulk density, and the influence of moisture content and particle size

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ABSTRACT

This research aimed at measuring the electrical capacitance of miscanthus biomass as a potential proxy measure of bulk density. The experimental arrangement allowed for continuous variation of bulk density through compression, whereas moisture content was varied at two levels, being air-dried (<5%) and oven dried (14.5%), and particle size was varied by using material that passed milling screen aperture sizes of 6.35, 9.53, 12.7, and 25.4 mm. A chamber was constructed containing the biomass, which was compressed using a hydraulic cylinder, causing the biomass bulk density to increase during the experiment. During the compression, the pressure applied vertically onto the biomass was inferred from the measured fluid pressure in the hydraulic cylinder. In addition, the displacement of the cylinder was measured using a linear encoder, allowing for instantaneous bulk density calculations.

Two capacitors, each comprising dual parallel flat copper plates, were fitted inside the chamber, where the biomass under compression acted as the dielectric medium. The conjecture was made that the force with which the biomass is pushed against the capacitor plates would highly influence the measured capacitance value, and therefore, one capacitor was placed in a longitudinal direction to capture vertical forces, and a second in the lateral direction to capture transverse forces.

The results showed a quasi-linear relationship between capacitance and bulk density. A proportional relationship was found between electrical capacitance and moisture content as well as between electrical capacitance and particle size. A comparison between vertical capacitance versus bulk density and the applied pressure versus bulk density showed that they are independent measurements. Therefore, the initial conjecture being that the force with which the biomass is pushed against the capacitance plates would have a large effect on the capacitance was deemed false; instead, the internal reorganization of biomass particles seems responsible for the variation in capacitance as observed.

The results imply that electrical capacitance may serve as a proxy for the measurement of miscanthus bulk density, but since moisture content and particle size have a marked effect on the capacitance, they must be determined separately or calibrated for. Currently, to determine the instantaneous moisture content of field crops, capacitor plates are already an integral part of yield monitoring systems. However, the method as investigated, adds the potential simultaneous measurement of the instantaneous bulk density of a biomass flow.

1. Introduction

Lignocellulosic biomass feedstock is a renewable resource that may contribute to reducing the world's dependence on fossil fuels (Miao et al., 2013a). The majority of the developed and developing countries have set biomass-based energy as a strategic priority of alternative energy. The Biomass R&D Technical Advisory Committee of the United States Congress has envisioned a 30% replacement of the current US petroleum consumption with biofuels by 2030 (Humbird et al., 2011; Perlack et al., 2013; Perlack and Stokes, 2011). In Canada, sustainable bioenergy development is one of six strategic priority areas for NRCan's Clean Energy Science and Technology Activity. In addition, the European Commission Directive 2009/28/EC has set the goal of using a minimum of 10%

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sustainable biofuels within the transportation sector of every member state by 2020. Finally, China, Japan, India and Brazil have also directed ample resources towards facilitating lignocellulosic biofuel research and commercialization.

Feedstock physical properties including particle size, shape, stiffness and strength, bulk density, flowability, and compressibility vary considerably among feedstock types, biomass forms, and production regions. These properties affect the feedstock behavior during handling/transportation, storage, pre-processing and either in direct combustion or during pre-treatment/conversion to liquid biofuel (Miao et al., 2013, 2013a,b, 2015). Currently, capacitance sensors are used for real time moisture content measurement as in modern grain yield monitors. This research showed that the same capacitance measurement principle could be used to estimate the bulk density of a flow of biomass in real time, which would be a valuable addition to the data flow in the biomass supply chain. In general, biomass feedstocks have low bulk densities due to their porous structure. Compression is used to increase biomass density, which lowers handling, transportation and storage costs, and promotes uniform combustion (Lin et al., 2015; Shastri et al., 2014; Stelte et al., 2012). Optimal transportation is present when the transportation medium reaches its volume and weight limits simultaneously. For instance, for long distance transportation of biomass in "gondola type" rail cars, a bulk density of 850 kg m^{-3}, is ideal because these cars are designed to precisely accommodate the bulk density of coal in a pile (Miao et al., 2013). An instrument that could determine the biomass bulk density in real-time, while taking into account moisture content and particle size distribution would therefore be useful.

Electrical properties such as resistance, conductivity, permittivity, and capacitance have been measured and studied for many years for foods (Jha et al., 2011) and other agricultural materials (Kim et al., 2003; Nelson, 1991, 2006). In addition, the complex dielectric constant, essentially the real part of the relative permittivity of materials, has been adopted to determine the ability of biomass feedstock to absorb and generate heat under microwave pretreatment (Ramasamy and Moghtaderi, 2010). Ground-penetrating radar (GPR) has also been used to study small root biomass effects on the dielectric properties of soil (Parsekian et al., 2011). Electrical properties of many agricultural materials are influenced by moisture content, density, temperature, chemical composition, and permanent dipole moment associated with water and other constituent molecules (Jones et al., 2006; Kim et al., 2003; Nelson, 1991, 2006; Ramasamy and Moghtaderi, 2010). The dielectric properties also depend on the frequency of the applied electric field, the temperature, density, and structure of materials (Lawrence et al., 2001; Nelson, 1991). A whole field of study is devoted to electrical properties of soils, evidenced by the use of commercially available soil conductivity based instruments being widespread (Kweon, 2012).

Electrical capacitance in particular has been used to measure the moisture content of nuts (Kandala et al., 2007), and to estimate root mass in a non-destructive fashion (Aulen and Shipley, 2012). They found that the relationship between capacitance and root dry mass was highly significant, but not accurate enough to meet the current needs for non-destructive root mass estimation. Capacitance sensors have also been used for biomass yield mapping of sugar beets and potatoes as well as to measure the throughput rate of a John Deere 750 forage harvest chopper for corn stover (Kumhala et al., 2010). However, few studies have focused on the measurement of biomass capacitance to infer bulk density of ground biomass as influenced by moisture content and particle size.

The capacitance equation of a parallel plate capacitor is a simple relationship, where the charge across the device in Coulomb is linearly related to the applied voltage and the capacitance value in Farad. The principal assumption here is that the dielectric properties and the dimensions of the capacitor remain constant, allowing for the theoretical value of the flat plate capacitor be calculated by integration of infinitesimal capacitance across the areas of the plates. However, the situation becomes far more complex if the value of the dielectric medium varies as is the case when it consists of biomass during compression. Here, the biomass can be regarded as an aggregate dielectric medium comprising a granular material, where the particles themselves have varying properties such as true density, shape, size, and electrical properties. During compression, they interact with each other and with the walls of the chamber, which changes their charge storage potential. These conflated influences offer little hope of ever truly understanding the underlying process, but nevertheless, preliminary tests showed three distinct phases during the compression, being (1) expulsion of air, where the particles are pushed closer together while occupying the void spaces, (2) particle reorientation where the void spaces are being filled by moving particles in contact with each other and the chamber walls, and (3) solid material behavior where all void spaces are occupied, and the aggregate material behaves like a quasi-solid. Fig. 1 shows a comparison in the capacitance progression for shelled corn (left) and shelled rice (right).

The three regions as mentioned are readily identifiable; the horizontal portion of the blue curve represents a near-constant capacitance, in the reorientation phase the capacitance shows a quasi-linear relationship with the height (bulk density) of the sample and the vertical part of the curve represents the behavior as a quasi-solid where the capacitance increases dramatically while the volume remains virtually constant. The curves also show the capacitance during rebound in red, where the rapid drop in capacitance indicates little or no elastic behavior of the materials.

In the tests with miscanthus, only the reorientation phase was studied, since it is the only phase where both the capacitance and the volume change during compression.

The objective of the research was to investigate whether the proxy measurement of electrical capacitance would be suitable to indirectly measure biomass bulk density, and to what extent moisture content and particle size influence the measurement.

2. Materials and methods

The miscanthus (Miscanthus × giganteus, Poaceae/Gramineae) material used in the research was planted at the Energy Farm of the University of Illinois at Urbana-Champaign in 2004 (lat, lon: 40.065799, −88.208599). The crop was harvested in the early spring of 2012. Miscanthus bales with a size of 1.2 × 1.2 × 2.4 m were stored for one year in a roofed open-air storage building at the Beef & Sheep Research Facility of the University of Illinois (lat, lon: 40.056112, −88.206735). Bales were chosen at random and broken up, producing samples consisting of approximately 70–80% stem material and 20–30% sheath and leaf material. Subsequently, the material was ground with a hammer mill (Model W-8-H, Schutte-Buffalo Hammer Mill, Buffalo, NY, USA) through screens with aperture sizes of 25.4, 12.7, 9.53, and 6.35 mm. To determine their moisture content, three replicates of 10–20 g biomass for each sample were dried for 24 h in an oven at 103 ± 3 °C, following the ASAE S358.2 DEC1988 (R2008) Standard for forage analysis.

To determine the effect of moisture content on electrical capacitance, samples were conditioned to two moisture content targets of 14.5% and less than 5%. This was accomplished by spraying water evenly over the ground particles, where the required amount of water was calculated based on sample weights and moisture content before conditioning. The conditioned samples were sealed in an impermeable bag at 22-25 °C for 72 h to achieve equilibrium moisture content (Miao et al., 2011, 2013b). The moisture content

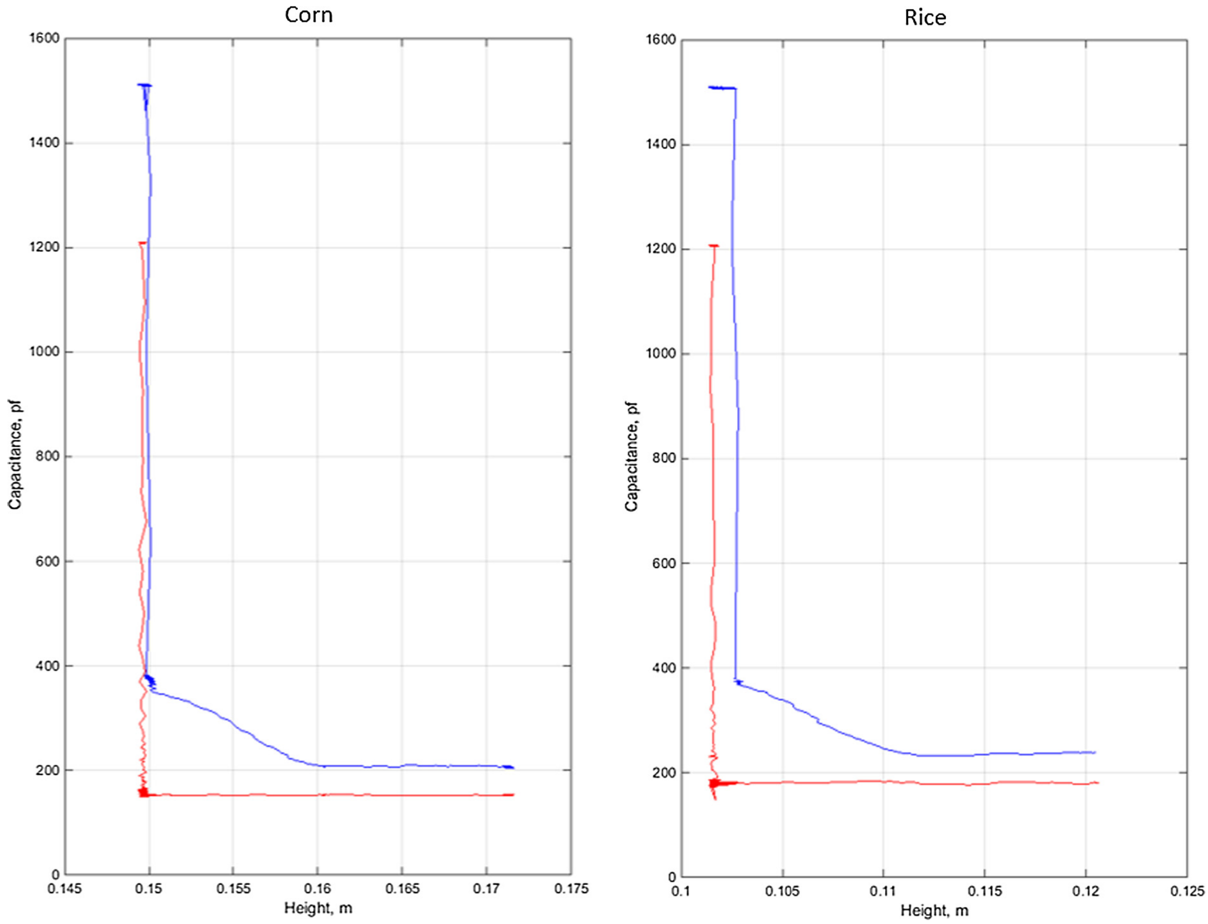

Fig. 1. Comparison of the capacitance progression as a function of sample height for corn (left) and rice (right). Three distinct regions can be recognized in each curve, being (1) expulsion of air, (2) particle reorientation, and (3) solid material behavior.

of the conditioned samples was also determined following the ASAE S358.2 DEC1988 (R2008) standard. The oven-dried samples were dried in an oven at a temperature of 49 °C for 72 h until the moisture content stabilized.

2.1. Biomass compression and electrical capacitance measurement

A hydraulic arrangement was used to measure the bulk density and electrical capacitance of biomass simultaneously during compression. A compression chamber with a volume of $150 \times 150 \times 203$ mm was constructed from steel tubing with a wall thickness of 6.35 mm (Fig. 2). During the tests, the pressure exerted onto the biomass was calculated from the hydraulic fluid pressure at the cap end of the cylinder, which was measured using a transducer (PX603-5KG5V, Omega Engineering Inc., Stamford, CT). The bulk density of the biomass was calculated from the displacement of the compression piston, which was measured using a linear potentiometer (LP801-300, Omega Engineering Inc., Stamford, CT). Details of the hydraulic compression arrangement are reported in earlier work (Miao et al., 2013b).

The electrical capacitance was measured using two pairs of parallel copper plates. One pair of vertical capacitor plates was mounted on rubber insulated backing plates that were placed underneath and on top of the biomass prior to compression. These identical capacitor plates had a dimension of 114.9×120.3 mm. A second pair of lateral capacitor plates was embedded into the bottom side wall of the compression chamber with insulating glue. The dimension of these lateral capacitor plates was 83.4×38.5 mm (Fig. 2).

The capacitance values of both the vertical and lateral capacitors were measured using two identical frequency-to-voltage converters or FVCs (LM2917, Texas Instruments) as shown in Fig. 2, whereas the schematic is shown in Fig. 3. The FVCs were driven by a sine wave with a frequency of 10.5 kHz and an amplitude of 5.3 V. In this configuration, the output voltage of the FVC has a linear relationship with the measured electrical capacitance CX (pin 2). The output voltages of the FVCs were measured using a data acquisition module (NI USB-6009) under control of MatLab® at a sampling rate of 1 kHz. The vertical and lateral capacitors were calibrated with ten 100-pf capacitors and one 1000-pf capacitor, which' values were measured using a dedicated capacitance meter (Velleman, model DVM 6013). The obtained calibration parameters were stored in a file that was read at the start of the data acquisition program.

2.2. Experimental design and procedure

A fractional factorial design was employed in the experiments, where the treatments comprised one crop (miscanthus), four particle sizes (material ground through screens with aperture sizes of 25.4 mm, 12.7 mm, 9.53 mm, and 6.35 mm) and two moisture content levels being oven-dried samples with a moisture content of <5% and moisture-conditioned samples with a moisture content of approximately 14.5%. Each experiment was repeated three times. Hereinafter, the particles ground through a milling screen

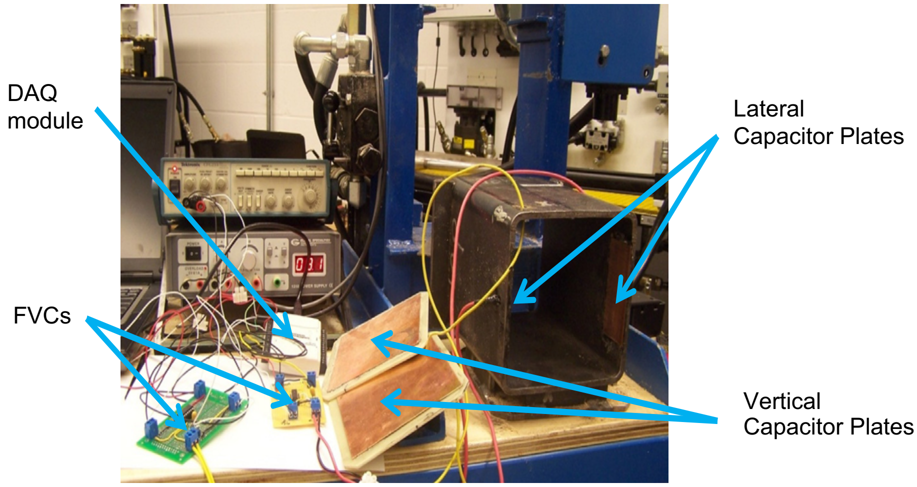

Fig. 2. Electric capacitance measurement arrangement comprising vertical and lateral capacitor plates in a compression chamber. Data acquisition was implemented using dual Frequency to Voltage Converters (FVCs using the LM2917), and a National Instruments NI6009 data acquisition module under control of MatLab®.

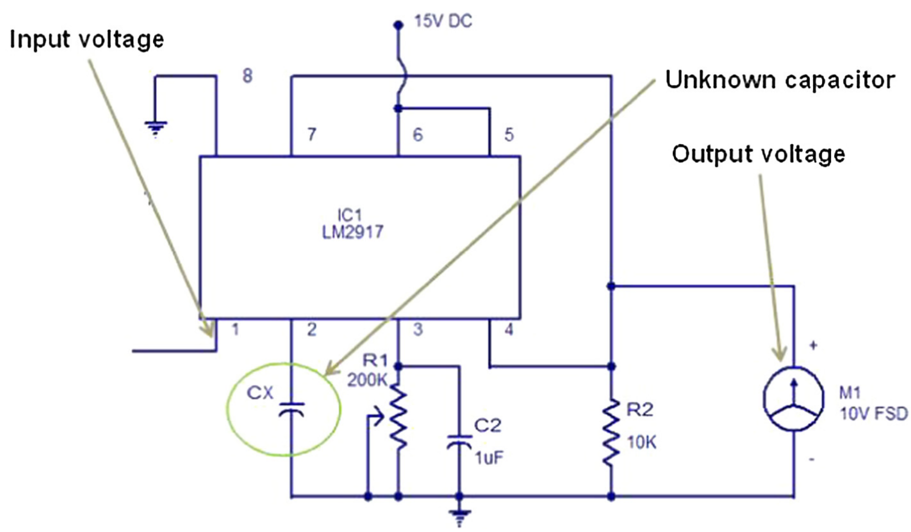

Fig. 3. Schematic of the LM2917 Frequency to Voltage Converter (FVC) in capacitance measurement mode.

with aperture size of 25.4, 12.7, 9.53, and 6.35 mm are abbreviated as 25.4-mm, 12.7-mm, 9.53-mm, and 6.35-mm particles, respectively.

For each experiment, 300 g of biomass was fed into the compression chamber, in which the bottom vertical capacitor plate had been placed in advance. The top vertical capacitor plate was placed onto the biomass after feeding the sample into the chamber. After placing a compression lid on the top vertical capacitor plate, the piston was pushed downward by the cylinder rod with an approximate speed of 10 mm per second. During compression, the cap end hydraulic oil pressure, piston position, as well as the vertical and lateral capacitance values were recorded for a duration of approximately 15 s. The experiments were conducted at a temperature of 22 ± 2 °C.

3. Results and discussion

Fig. 4 shows the relationship between measured vertical capacitance in pf versus the bulk density in kg DM m^{-3}, as well as the pressure applied to the biomass in MPa versus the bulk density in kg DM m^{-3} for both an ovendried sample and one with a moisture content of approximately 14.5%. Note that the maximum pressure applied to both samples was 1.29 MPa. The relationship between applied pressure and bulk density exhibited a power law form, a phenomenon that was encountered numerous times in earlier research (Miao et al., 2012, 2013, 2013b, 2015). At the maximum applied pressure of 1.29 MPa the ovendried sample reached a bulk density of approximately 325 kg DM m^{-3}, whereas the sample with a moisture content of 14.5% reached a bulk density of approximately 380 kg DM m^{-3}. At the maximum applied pressure of 1.29 MPa the ovendried sample reached a capacitance value of approximately 160 pf, whereas the sample with a moisture content of 14.5% reached a capacity of approximately 215 pf.

Comparing the capacitance (blue[2]) and pressure curves (red), it is clear that these are independent measurements. Initially, the conjecture was made that the capacitance value of the dielectric biomass would be related to the pressure with which it is pushed against the capacitor plates, but these results refute this idea: the difference in capacitance must be attributed to internal changes in the particle configuration, and particle-particle and particle-wall contact areas associated with it. As expected, the capacitance

[2] For interpretation of color in Fig. 5, the reader is referred to the web version of this article.

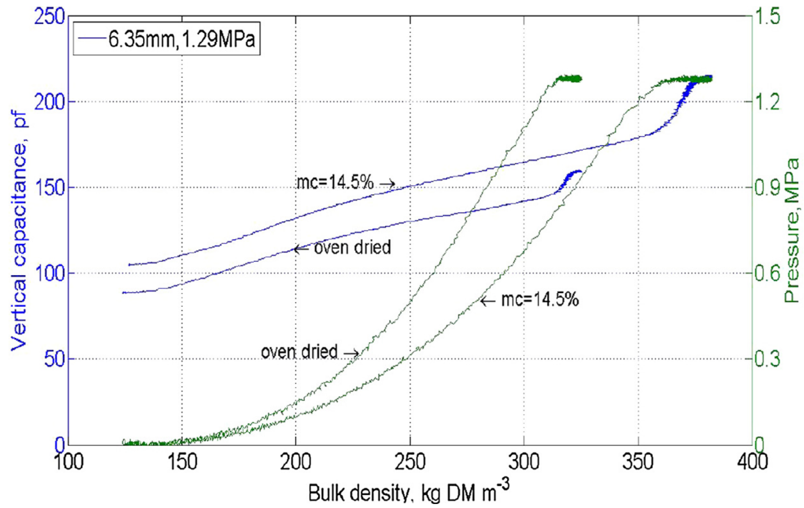

Fig. 4. Relationship between the capacitance in pf (from the vertical capacitor) and the bulk density in kg DM m^{-3} for 6.35 mm particles, at a moisture level of <5% (oven dried) and approximately 14.5%. The maximum pressure applied to the biomass was 1.29 MPa. Note that the curves shown are the means among three experiments.

progression is offset due to the difference in moisture content between the samples, but the overall shape of the curves is highly similar. Although some curvature is present, for practical purposes, they can be regarded as a linear function, which is attractive from the point of sensor development, in contrast to the power-law relationship between the applied pressure and bulk density. In addition, an increase in moisture content causes a simple offset in the capacitance measurement, whereas in this case, the pressure curves exhibit an incremental deviation. Earlier studies have shown how the moisture content of biomass influences the applied pressure needed to reach a certain bulk density (Miao et al., 2013b).

Fig. 5 shows the effect of particle size on the capacitance progression in pf versus the bulk density in kg DM m^{-3}, where all miscanthus materials were oven dried, and compressed to a pressure of 1.29 MPa. Both the lateral and vertical capacitance values are shown. The initial capacitance of the vertical capacitor was much higher than that of the lateral capacitor, but the overall shape of the curves was similar, particularly for bulk density values higher than 200 kg DM m^{-3}. In addition, the vertical capacitor curves have a more consistent, linear relationship with bulk density than the lateral capacitor curves. This is caused by the fact that due to their location, the biomass is always in mere partial contact with the lat-

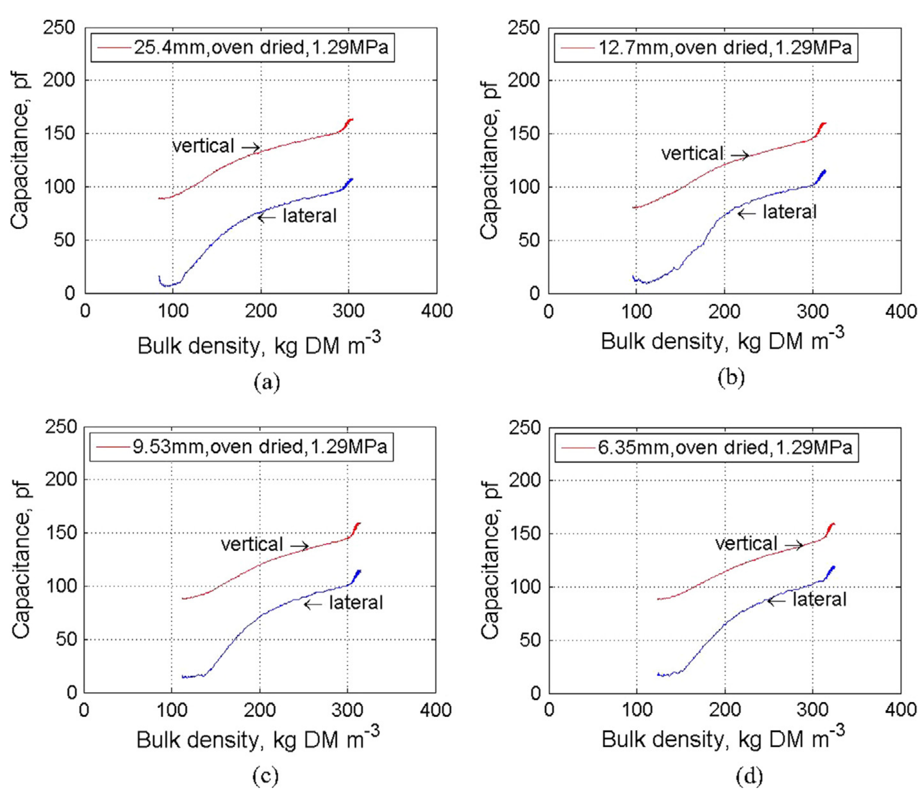

Fig. 5. Subplots (a), (b), (c), and (d) illustrate the relationship between the vertical and lateral capacitor values for particle diameters in the range 25.4, 12.7, 9.53, and 6.35 mm, at a constant moisture content (oven dried).

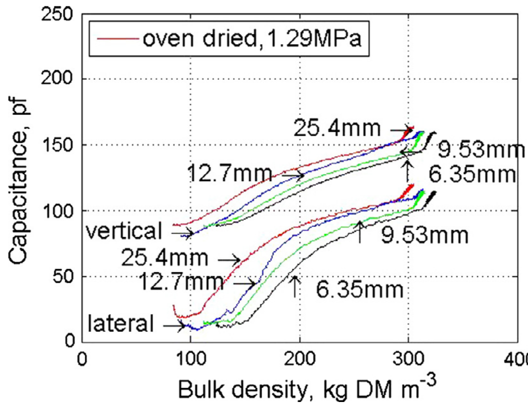

Fig. 6. Summary plot showing vertical and lateral capacitor curves for particle sizes in the range 25.4, 12.7, 9.53 and 6.35 mm, for oven dried biomass compressed to 1.29 MPa. Note that the vertical capacitance data is more consistent and linear than the lateral capacitor data, which had limited contact with the biomass at all times.

eral capacitor plates. In addition, earlier, the idea that the pressure exerted by the biomass onto the capacitor plates affects the capacitance value was already refuted, which is confirmed here: In earlier research, Poisson's ratios of miscanthus and switchgrass ranged from 0.2 to 0.3 for various particle sizes (Miao et al., 2015), whereas the ratios between the vertical and lateral capacitance values as found here are much higher. Therefore a proposed proportionality between applied pressure and capacitance would not be feasible.

For comparison, Fig. 6 shows all the curves presented in Fig. 5 in a single graph. It is clear that the capacitance values of the vertical capacitor are higher than those of the lateral capacitor, and that each set of curves shows a consistent increase of capacitance with particle size.

4. Conclusions

As a proxy measurement for bulk density in kg DM m^{-3}, miscanthus biomass electrical capacitance in pf was measured in a compression arrangement for two moisture content levels being oven-dried (<5%) and moisture-conditioned (14.5%) and materials ground through screens with aperture sizes of 25.4 mm, 12.7 mm, 9.53 mm, and 6.35 mm. The arrangement was fitted with a vertical capacitor as well as a lateral capacitor embedded into the sidewalls of the compression chamber.

Although the underlying process causing the change in capacitance in a granular material during compression is beyond current understanding, three distinct phases were identified during compression of corn and rice being (1) air expulsion, where the capacitance remains constant while air is being expelled, (2) particle reorientation, where particles move and occupy voids, yielding a quasi-linear relationship between capacitance and bulk density and (3) solid material behavior, where the capacitance increases rapidly with little change in bulk density. The experiments with biomass only observed phase 2 behavior.

The results showed quasi-linear relationships between electrical capacitance in pf versus bulk density in kg DM m^{-3}, among all measurements. This is in contrast to the relationship between applied pressure in MPa versus bulk density in kg DM m^{-3}, which was known and confirmed to be a power law relationship.

The capacitance versus bulk density data from the vertical capacitor were more consistent and linear than those of the lateral capacitor. This is due to the fact that during compression the biomass is always in full contact with the vertical capacitor plates, but only in partial contact with the lateral capacitor plates. For this reason, such use of lateral capacitor plates is not recommended.

The capacitance measurement principle as developed has an advantage over alternatives in that it produces quasi-linear relationships between electrical capacitance and bulk density. However, the experiments showed that the measured capacitance was proportional to both moisture content as well as particle size. In contrast to bulk density, these could not be varied continuously, therefore their influences were assessed based on limited data. In practice, while using electrical capacitance as a proxy for bulk density, for accurate measurements, these would have to be determined separately.

The next logical step in future research is to extend the concept of biomass capacitance measurement to impedance spectroscopy, where, during compression, the real and imaginary parts of the material impedance are determined for a range of frequencies. The data created will aid in understanding the underlying process that causes the emergence of the three phases as observed in this research, as well as in a more detailed material characterization.

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